UNCLASSIFIED

AD 269 129

Reproduced
by the

ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA
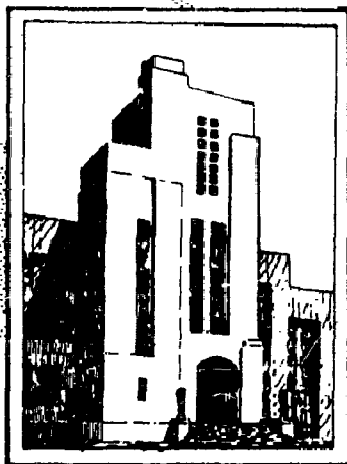
UNCLASSIFIED

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN

HYDROMECHANICS

○

AERODYNAMICS

○

STRUCTURAL
MECHANICS

○

APPLIED
MATHEMATICS

PERFORMANCE OF VERTICAL AXIS (CYCLOIDAL) PROPELLERS
CALCULATED BY TANIGUCHI'S METHOD

by

W.L. Haberman and E.E. Harley

HYDROMECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

November 1961   Report 1564

PERFORMANCE OF VERTICAL AXIS (CYCLOIDAL) PROPELLERS
CALCULATED BY TANIGUCHI'S METHOD

by

W.L. Haberman and E.E. Harley

November 1961

TABLE OF CONTENTS

LIST OF FIGURES

NOTATION

a_o	Blade section lift-curve slope
b	Blade length
c	Blade chord
c_s	Blade chord at root
c_d	Blade section drag coefficient
c_{do}	Blade section drag coefficient at zero lift
c_1	Blade section lift coefficient
d	Blade section drag
D	Orbit diameter $(= 2R)$
e	Propeller efficiency $\left(= \dfrac{K_T}{K_Q}\, \dfrac{\lambda}{2}\right)$
I_1, I_2, I_3	Integrals, defined on page 5
k	Constant in expression for blade section drag coefficient
K_T	Propeller thrust coefficient $\left(= \dfrac{T}{\rho n^2 D^3 b}\right)$
K_Q	Propeller torque coefficient $\left(= \dfrac{Q}{\rho n^2 D^4 b}\right)$
1	Blade section lift (in direction perpendicular to resultant velocity v)
m	Moment about orbit origin acting on each blade section
n	Revolutions per unit time
Q	Total torque of propeller
R	Orbit radius
t	Blade section thrust
$T(\theta)$	Instantaneous thrust of blade
T_{av}	Average thrust of blade of propeller
T	Total thrust of propeller
u_i	Induced velocity component in direction of advance
u_o	Speed of advance of propeller

v	Resultant velocity of fluid past blade section
z	Number of propeller blades
α	Angle of attack of blade section measured from angle of zero lift
η	Eccentricity setting of propeller
θ	Blade orbit angle
κ	Correction factor in momentum relation
λ	Advance coefficient $\left(= \dfrac{u_o}{n \pi D}\right)$
λ_i	Induced velocity factor
ρ	Density of fluid
σ	Solidity $\left(= \dfrac{z\, c_s}{\pi D}\right)$
φ	Blade angle
ω	Angular velocity $(= n \pi D)$

ABSTRACT

A method proposed by Taniguchi has been used to compute the performance characteristics of vertical axis propellers having cycloidal blade motion and semi-elliptic blades. Numerical results of thrust and torque coefficient and efficiency are presented for a wide range of advance coefficients, maximum blade angle, and blade solidity.

Good agreement between the experimental performance and the computed results is obtained for two, three, and six-bladed cycloidal propellers.

INTRODUCTION

In a series of three papers, Taniguchi presented a method for numerically evaluating the performance characteristics of vertical axis propellers.[1,2,3] In the first paper he derived expressions for the thrust, torque, and efficiency of a vertical axis propeller based on certain simplifying assumptions and estimates. After conducting experiments with a six-bladed vertical axis propeller he modified the earlier expressions for the propeller performance. The final form of the computational method proposed by Taniguchi was presented in detail as a doctoral thesis.[3]

To assess the validity of Taniguchi's method over a wide range of conditions, computations were carried out at the David Taylor Model Basin using his method. The results of the DTMB computations were compared with available data from DTMB experimental investigations on two, three, and six-bladed cycloidal propellers. In addition, numerical evaluation of propeller performance characteristics were carried out over a large range of propeller eccentricity and blade solidity. The results of all the computations and the comparison are presented in graphical form.

OUTLINE OF TANIGUCHI'S METHOD

The method proposed by Taniguchi for computing the performance characteristics of vertical axis propellers is based on the assumption that quasi-steady state motion exists.* The total thrust and torque of the propeller

---

[1] References are listed on page 10.

* An attempted unsteady theory for vertical axis propellers was analyzed in a recent report.[4]

is evaluated by integrating the lift and drag forces exerted on each blade
section. For this purpose numerical values of lift and drag coefficients
of the blade sections are required. In addition, an estimate of the mag-
nitude and direction of the induced velocity at every blade section must
be made. Taniguchi assumed (1) that only the longitudinal velocities
induced by the trailing vortex system (i.e., those in the direction of
propeller advance) contribute to the thrust and torque of the propeller,
(2) that they are of constant magnitude over the length of blade, (3) that
the induced velocity is not a function of the orbital position of the blade.
The value of the induced velocity is obtained from momentum considerations
with modifications based on experimental performance of a six-bladed vertical
axis propeller.

The details of the derivation of Taniguchi's method are as follows:

Each propeller blade is assumed to rotate with constant angular
velocity about the center "0" which advances at constant speed u_o
(Figure 1). As a consequence of the motion, the fluid exerts a force on each
section of the blade. This force can be resolved into two components: the
section lift force and the section drag force. These forces can be expressed
in terms of the force coefficient and dynamic head, namely

$$\ell = c_\ell \frac{\rho}{2} v^2 c$$

$$d = c_d \frac{\rho}{2} v^2 c$$

where the lift is in a direction perpendicular to the resultant field
velocity past each blade section, while the drag is parallel to the resultant
velocity.

Taking the components of the lift and drag force on the blade section
in the direction of forward motion of the propeller, the thrust force due to
each blade section is obtained:

$$t = \ell \cos(\theta - \varphi + \alpha) + d \sin(\theta - \varphi + \alpha)$$

where θ is the blade orbit angle, φ is the blade angle, and α is the
angle of attack of blade section. For most of the orbital positions of the
blade, the drag contribution to the section thrust will be small in com-
parison to the lift contribution. An exception occurs at orbit angles in
the neighborhood of 90 and 270 degrees. Since the integrated effect over
the entire orbit is of concern here, Taniguchi neglected the drag term. Thus

6

$$t = c_l \tfrac{\rho}{2} v^2 c \cos(\theta - \varphi + \alpha)$$

The moment about the propeller origin acting on each blade section is (see Figure 2)

$$m = l \cos(\theta - \varphi + \alpha) R \sin \theta - l \sin(\theta - \varphi + \alpha) R \cos \theta$$
$$+ d \cos(90 - \theta + \varphi - \alpha) R \sin \theta + d \sin(90 - \theta + \varphi - \alpha) R \cos \theta$$

Using trigonometric simplification, we obtain

$$m = l R \sin(\varphi - \alpha) + d R \cos(\varphi - \alpha)$$
$$m = \tfrac{\rho}{2} v^2 c R \left[c_l \sin(\varphi - \alpha) + c_d \cos(\varphi - \alpha) \right]$$

To obtain quantitative evaluation of propeller performance, values must now be assigned to these coefficients. In his earlier paper,[1] Taniguchi used the following values for the drag and lift coefficient:

$$c_l = a_o \alpha = 5.34 \alpha \qquad (\alpha \text{ in radians})$$
$$c_d = c_{do} + k \alpha^4 = 0.10 + 6 \alpha^4$$

These values were based on averages obtained from wind tunnel tests on airfoil sections. In his second paper,[2] Taniguchi revised the expression for the drag coefficient based on the experiments conducted by him on six-bladed cycloidal propellers with semi-elliptic blade outline. The revised expression is as follows:

$$c_d = c_{do} + k \alpha^2 = 0.019 + 2.24 \alpha^2$$

Substituting into the expression for thrust and moment of the blade section we obtain

$$t = \tfrac{\rho}{2} v^2 c \, a_o \alpha \cos(\theta - \varphi + \alpha)$$

and

$$m = \tfrac{\rho}{2} v^2 c R \left[a_o \alpha \sin(\varphi - \alpha) + (c_{do} + k \alpha^2) \cos(\varphi - \alpha) \right]$$

To evaluate the thrust and torque of a given propeller, the following relationships must be known:

(1) The variation of resultant velocity (v) at each blade section with blade orbit angle (θ).

(2) The variation of blade angle (φ) with blade orbit angle (θ). From a knowledge of v and φ at every blade orbit position, we can derive a relationship between angle of attack of blade (α) and orbit angle (θ).

In evaluating the resultant velocity v past each blade section, Taniguchi included only the induced velocity in the direction of forward motion of the propeller. Thus he takes

$$v^2 = (n \pi D)^2 + (u_0 + u_i)^2 - 2(u_0 + u_i) n \pi D \sin \theta$$

Dividing by $(n \pi D)^2$ we obtain

$$\left(\frac{v}{n \pi D}\right)^2 = 1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta$$

He further assumed that the induced velocity is constant over the entire length of blade and is independent of blade orbit position.

For cycloidal blade motion, the tangent of the blade angle varies with the orbit angle in the following manner:

$$\tan \varphi = \frac{\eta \cos \theta}{1 - \eta \sin \theta}$$

where η is the eccentricity setting of the propeller and is related to the maximum blade angle as indicated in Figure 3.

By appropriate substitution we obtain an expression for $\cos(\theta - \varphi + \alpha)$ in terms of θ, λ, and λ_i, namely

$$\cos(\theta - \varphi + \alpha) = \pm \frac{\cos \theta}{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}$$

Where the positive signs applies to values of θ between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$, while the negative sign applies to values of θ between $\frac{\pi}{2}$ and $\frac{3}{2}\pi$. By further substitution, we obtain the following relation between angle of attack (α) of the blade section and blade orbit angle (θ):

$$\tan \alpha = \pm \frac{(\eta - \lambda - \lambda_i) \cos \theta}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta}$$

where the same sign convention as given above holds. For small angles α i.e., for angles of attack below the stall angle (12 to 16 degrees), $\tan \alpha \cong \alpha$. Thus the section thrust at a given orbit position is

$$t = \frac{1}{2} a_0 c (\pi n D)^2 (\eta - \lambda - \lambda_i) \frac{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta} \cos^2 \theta$$

The thrust of each blade at a given orbital position is then obtained by integrating over the blade length. Thus

$$T(\theta) = \int_0^b t \, db$$

For blades with semi-elliptic outline, the thrust of each blade becomes

$$T(\theta) = \frac{\pi}{8} \rho a_0 c_0 b n^2 D^2 (\eta - \lambda - \lambda_i) \frac{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta} \cos^2 \theta$$

With the assumption of constant induced velocity and symmetry of blade motion (Figure 3), the thrust of each blade is symmetric in the forward and aft half of the orbit. To obtain the average thrust of each blade (T_{av}), we need to average over half of the orbit only. Thus

4

$$T_{av} = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} T(\theta)\,d\theta = \frac{\pi^2}{8}\rho\, a_0\, c_s\, b\, n^2 D^2 (\eta - \lambda - \lambda_i)\int_{-\pi/2}^{\pi/2}\frac{\sqrt{1+(\lambda+\lambda_i)^2 - 2(\lambda+\lambda_i)\sin\theta}}{1+\eta(\lambda+\lambda_i)-(\eta+\lambda+\lambda_i)\sin\theta}\cos^2\theta\,d\theta$$

The total thrust of the propeller is then obtained by multiplying by the number of blades

$$T = z\, T_{av}$$

The moment of the blade section about the propeller origin becomes

$$m = \tfrac{1}{2} c \frac{D}{2}(\pi n D)^2 \Big[a_0 (\lambda+\lambda_i)(\eta-\lambda-\lambda_i)\frac{\sqrt{1+(\lambda+\lambda_i)^2 - 2(\lambda+\lambda_i)\sin\theta}}{1+\eta(\lambda+\lambda_i)-(\eta+\lambda+\lambda_i)\sin\theta}\cos^2\theta$$
$$+ c_{do}\{1-(\lambda+\lambda_i)\sin\theta\}\sqrt{1+(\lambda+\lambda_i)^2-2(\lambda+\lambda_i)\sin\theta}$$
$$+ k(\eta-\lambda-\lambda_i)^2\{1-(\lambda+\lambda_i)\sin\theta\}\frac{\sqrt{1+(\lambda+\lambda_i)^2 - 2(\lambda+\lambda_i)\sin\theta}}{\{1+\eta(\lambda+\lambda_i)-(\eta+\lambda+\lambda_i)\sin\theta\}^2}\cos^2\theta\Big]$$

The total torque of the propeller is then given by

$$Q = z\,\frac{1}{\pi}\int_{-\pi/2}^{\pi/2}\int_0^b m\, db\, d\theta$$

For brevity, let

$$I_1 = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2}\frac{\sqrt{1+(\lambda+\lambda_i)^2 - 2(\lambda+\lambda_i)\sin\theta}}{1+\eta(\lambda+\lambda_i)-(\eta+\lambda+\lambda_i)\sin\theta}\cos^2\theta\,d\theta$$

$$I_2 = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2}\{1-(\lambda+\lambda_i)\sin\theta\}\sqrt{1+(\lambda+\lambda_i)^2-2(\lambda+\lambda_i)\sin\theta}\,d\theta$$

$$I_3 = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2}\frac{\{1-(\lambda+\lambda_i)\sin\theta\}\sqrt{1+(\lambda+\lambda_i)^2-2(\lambda+\lambda_i)\sin\theta}}{\{1+\eta(\lambda+\lambda_i)-(\eta+\lambda+\lambda_i)\sin\theta\}^2}\cos^2\theta\,d\theta$$

The thrust and torque of the propeller therefore become

$$T = \frac{\pi^3}{8} z\,\rho\, c_s\, b\, n^2 D^2 a_0 (\eta-\lambda-\lambda_i) I_1$$
$$Q = \frac{\pi^3}{16} z\,\rho\, c_s\, b\, n^2 D^3 \Big[a_0 (\lambda+\lambda_i)(\eta-\lambda-\lambda_i) I_1 + c_{do} I_2 + k(\eta-\lambda-\lambda_i)^2 I_3\Big]$$

Define the thrust and torque coefficients as follows:

$$K_T = \frac{T}{\rho n^2 D^3 b}$$

and

$$K_Q = \frac{Q}{\rho n^2 D^4 b}$$

In addition, let $\sigma = \frac{z c_s}{\pi D}$ be the solidity of the blades. We, therefore, obtain the following expressions for the thrust and torque coefficient

$$K_T = \frac{\pi^4}{8} a_0\,\sigma\,(\eta-\lambda-\lambda_i) I_1$$

$$K_Q = \frac{\lambda+\lambda_i}{2} K_T + \frac{\pi^4}{16}\sigma\Big[c_{do} I_2 + k(\eta-\lambda-\lambda_i)^2 I_3\Big]$$

5

Further the propeller efficiency is given by

$$e = \frac{K_T}{K_Q} \frac{\lambda}{2}$$

The integrals I_1, I_2, and I_3 can be evaluated numerically for values of eccentricity, advance coefficient and induced velocity factor. There now remains the problem of estimating values of the induced velocity factor. To obtain this estimate, Taniguchi used a momentum relation, namely

$$T = 2\rho D b \frac{u_o + u_i}{\kappa} \left[\frac{u_o + u_i}{\kappa} - u_o \right]$$

Nondimensionalizing we obtain

$$K_T = 2\pi^2 \frac{\lambda + \lambda_i}{\kappa} \left[\frac{\lambda + \lambda_i}{\kappa} - \lambda \right]$$

where κ is a correction factor to account for non-uniformity of induced velocity over the blade length. In Reference 1, Taniguchi estimated the value of κ as 1.176. After conducting experiments on a six-bladed propeller, and obtaining a large discrepancy between computed and experimental values of advance coefficient at zero thrust, Taniguchi modified the momentum relation for K_T to

$$K_T = \frac{2\pi^2}{\kappa} (\lambda + \lambda_i) \lambda_i$$

The factor κ is now a projected area reduction factor. This modification resulted in a revised value of κ, namely 1.321.

Values of induced velocity factor as a function of propeller thrust coefficient for various advance coefficient are given in Figure 4.

To obtain performance characteristics of a propeller, of specified solidity over a range of advance coefficients, the two expressions for K_T must be solved simultaneously. This is done by graphical solution as indicated by the example shown in Figure 5, where the two expressions for thrust coefficient have been plotted for an eccentricity of 0.7 over a range of solidity and advance coefficient. The intersection of the σ = constant and λ = constant curves gives the value of thrust coefficient desired.

Using his revised values for section drag coefficient and κ, Taniguchi computed[2] the performance characteristics of vertical axis propellers with semi-elliptic blade outline and solidity of 0.40.

6

RESULTS OF DTMB NUMERICAL EVALUATIONS

Using the procedure outlined above and the revised values of section
drag coefficient and induced velocity factor, the thrust coefficient, torque
coefficient and efficiency of vertical axis propellers with cycloidal blade
motion and semi-elliptic blade outline were evaluated by the David Taylor
Model Basin over a range of advance coefficients, maximum blade angles
(eccentricities), and solidities. The results of these computations are
given in Figures 6 and 7. Propeller performance at values of eccentricity
and solidity other than those given in the figures can easily be obtained
by cross plotting.

As seen in the figures, the performance characteristics were evaluated
at eccentricities up to 0.95. It is clear, however, that in some cases the
angles of attack will be large and the angle of stall will be exceeded.
Since small angles of attack were assumed in the derivation and since reduced
lift characteristics of the blade sections are obtained for angle of attack
exceeding the stall angle, reliable predictions of the performance charac-
teristics cannot be expected for those cases. To illustrate this limitation,
a typical variation of the angle of attack with blade orbit angle is shown
in Figure 8. From the expression for α given in the preceding section, it
is seen that for a given eccentricity, the maximum angle of attack always
occurs at zero advance coefficient. Thus, values of maximum at zero
advance were computed over a range of eccentricity and solidity and are
given in Figure 9.

From Figures 6 and 7 it is further seen that the total thrust, torque
and maximum efficiency of the cycloidal propellers increase with increase
in maximum blade angle. For increase in blade solidity, the total thrust
and torque increases. However, the thrust and torque of each blade and the
maximum efficiency of the propeller decrease with increase in number of
blades of same dimensions. Such decrease in thrust per blade and efficiency
is also characteristic of screw propellers (see e.g. Reference 5).

COMPARISON WITH DTMB EXPERIMENTS

A comparison was made between the results of the DTMB computations using Taniguchi's method and DTMB experimental measurements of the performance of vertical axis propellers with blades having semi-elliptic outline. The experiments were conducted with propellers having two, three, and six identical blades. Cycloidal blade motion was used in the experiments with eccentricity settings of 0.4 and 0.6.* The aspect ratio of the DTMB blades was the same as Taniguchi used in his experiments. The comparison between experimental and computational results is shown in Figures 10 and 11. It is seen from the figures that good agreement is obtained between the computed and experimental values of propeller performance. Of particular interest is the good prediction of the effect of varying the number of blades on the propeller.

The correction factor ($\varkappa$) and section drag characteristics (c_{do}, k) were evaluated by Taniguchi at the zero advance condition. He obtained an average value of 1.321 based on his experimental results of a six-bladed propeller at four different eccentricity settings. Table 1 gives values of $\varkappa$ evaluated from the results of the DTMB experiments.

TABLE 1

Evaluation of $\varkappa$

η	0.4			0.6		
z	2	3	6	2	3	6
K_T(exp)	0.70	0.86	1.13	1.22	1.56	2.13
λ_i (exp)	0.212	0.240	0.277	0.287	0.323	0.375
$\varkappa$	1.264	1.312	1.340	1.332	1.312	1.303
Av. $\varkappa$	1.305			1.315		

---

* The results of the DTMB experimental investigation, in which blade motion and blade outline was varied, will be reported in detail in a forthcoming report.

In Table 2, the quantities used to evaluate the section drag characteristics are given. A plot of these quantities is also shown in Figure 12.

TABLE 2

Evaluation of Section Drag Coefficient

η	0.4			0.6		
z	2	3	6	2	3	6
K_T(exp)	0.70	0.86	1.13	1.22	1.56	2.13
K_Q(exp)	0.12	0.16	0.219	0.32	0.40	0.58
$\lambda+\lambda_i$ (comp)	0.212	0.240	0.277	0.287	0.323	0.375
I_2(comp)	1.034	1.043	1.057	1.062	1.077	1.105
I_3(comp)	0.506	0.500	0.492	0.535	0.520	0.497
$16\dfrac{K_Q-\frac{1}{2}(\lambda+\lambda_i)K_T}{\pi^4\sigma\,I_2}$	0.0547	0.0445	0.0243	0.1685	0.1124	0.06711
$(\eta-\lambda-\lambda_i)^2\,I_3/I_2$	0.0173	0.0123	0.00703	0.0494	0.0370	0.0229

CONCLUSIONS

The computational procedure proposed by Taniguchi for evaluating the performance characteristics of vertical axis propellers is adequate for propellers with cycloidal blade motion and semi-elliptic blades. For this type of propeller the procedure gives satisfactory prediction of the effect of number of blades on propeller performance.

For each blade motion other than cycloidal motion, experimental results are required to obtain new values of the correction factor κ . In addition, large changes in aspect ratio of the blade will affect the mag-nitude of the correction factor. Further, significant variation in blade motion would probably result in different values of the section character-istics.

In summary, the most serious limitation of Taniguchi's method lies in the way the induced velocities are estimated; specifically, in the assumption that only the longitudinal components contribute to propeller

performance, in the assumption that the induced velocity is constant over the entire length of the blade, and finally in the fact that the induced velocity cannot be computed without resorting to determination by experiment.

REFERENCES

1. Taniguchi, K., "An Approximate Solution of the Voith-Schneider Propeller", Jl of Zosen Kiokai (Trans. Soc. of Naval Arch. of Japan) Vol. 74 (1944) pp 153-161.

2. Taniguchi, K., "Hydrodynamical Investigations of the Blade Wheel Propeller", Jl of Zosen Kiokai, Vol. 88 (1950) pp 63-74.

3. Taniguchi, K., "Studies on a Trochoidal Propeller", Doctor of Engineering Thesis, Tokyo University (1960).

4. Haberman, W.L. and Caster, E.B., "Performance of Vertical Axis (Cycloidal) Propellers According to Isay's Theory", International Shipbuilding Progress (in publication); or David Taylor Model Basin Hydromechanics Laboratory TN 31 (Mar 1961).

5. Morgan, W.B., "Open Water Test Series of a Controllable Pitch Propeller with Varying Number of Blades", David Taylor Model Basin Report 932 (Nov 1954).
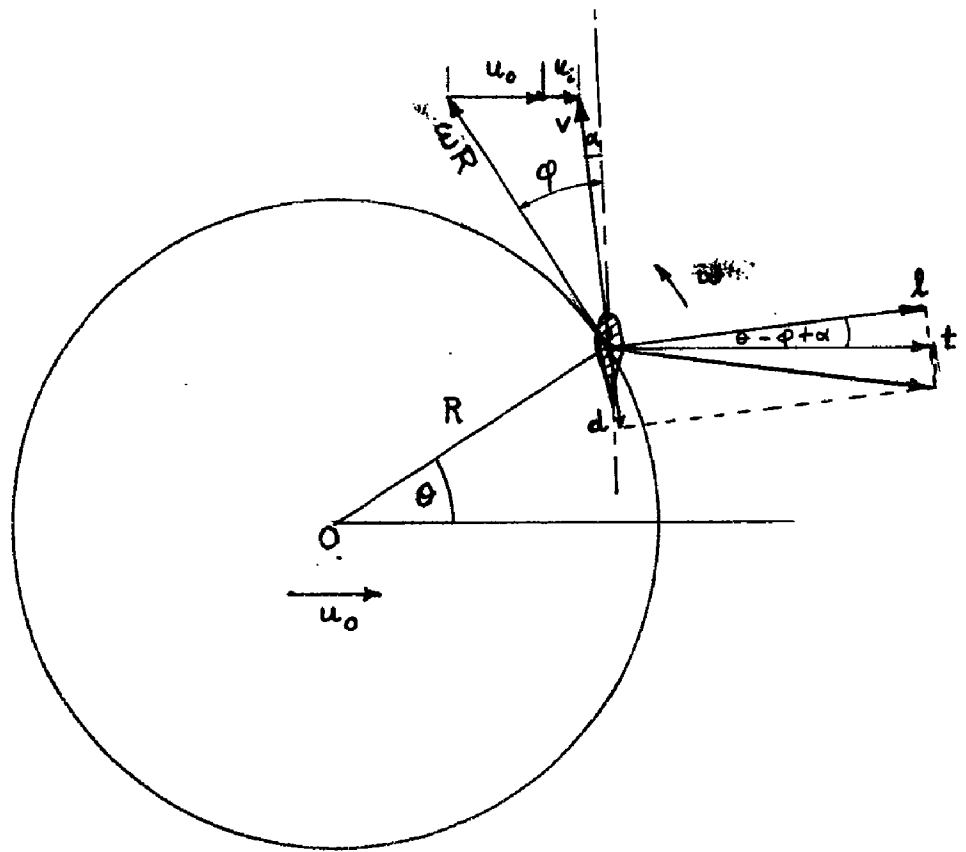
Figure 1 - Sketch of Blade Section Showing Forces Exerted
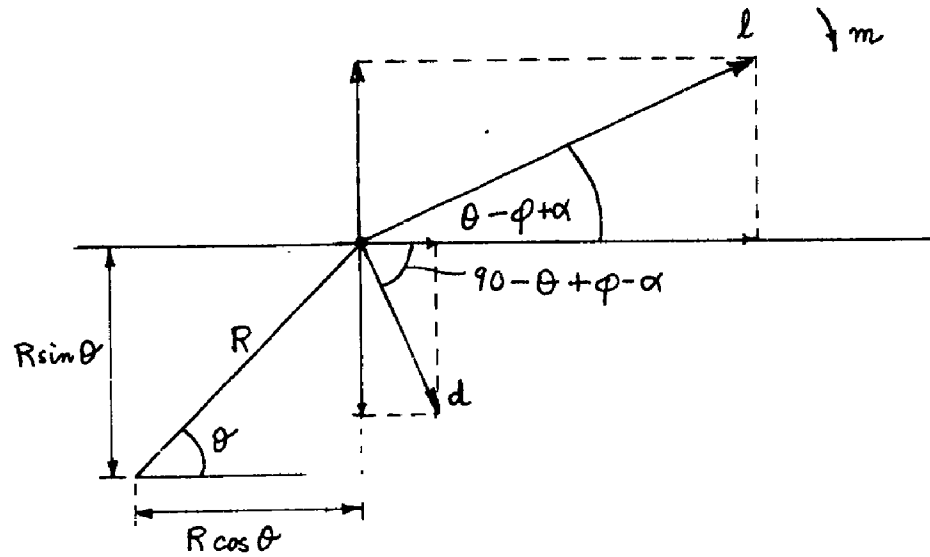
Figure 2 - Sketch of Blade Force System

11
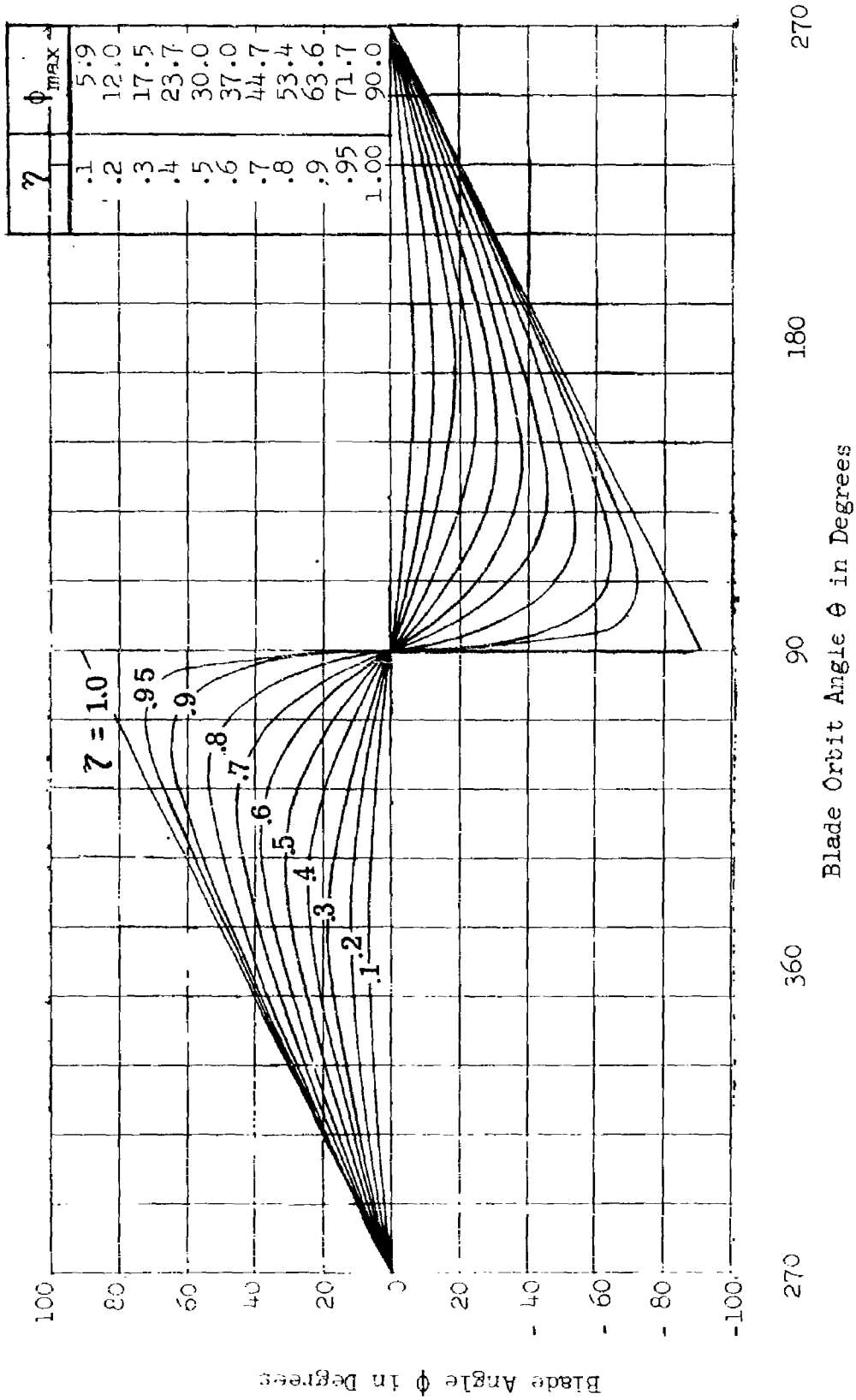
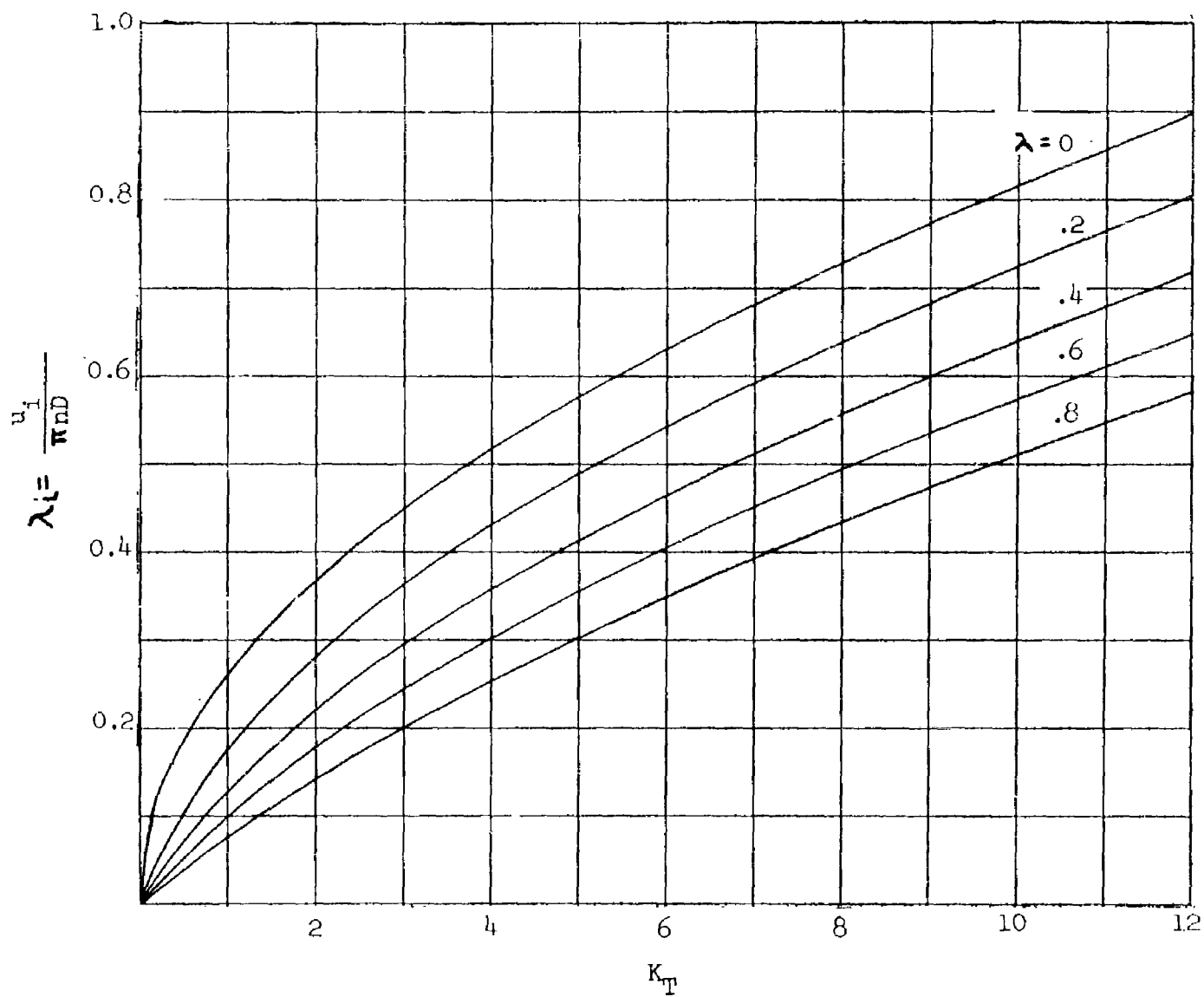Figure 3 — Variation of Blade Angle with Blade Orbital Position for Various Eccentricities

η	ϕ_{MAX}
.1	5.9
.2	12.0
.3	17.5
.4	23.7
.5	30.0
.6	37.0
.7	44.7
.8	53.4
.9	63.6
.95	71.7
1.00	90.0

Blade Orbit Angle θ in Degrees

Blade Angle ϕ in Degrees

Figure 4 – Longitudinal Induced Velocity as a Function of Thrust Coefficient
for Various Advance Coefficients
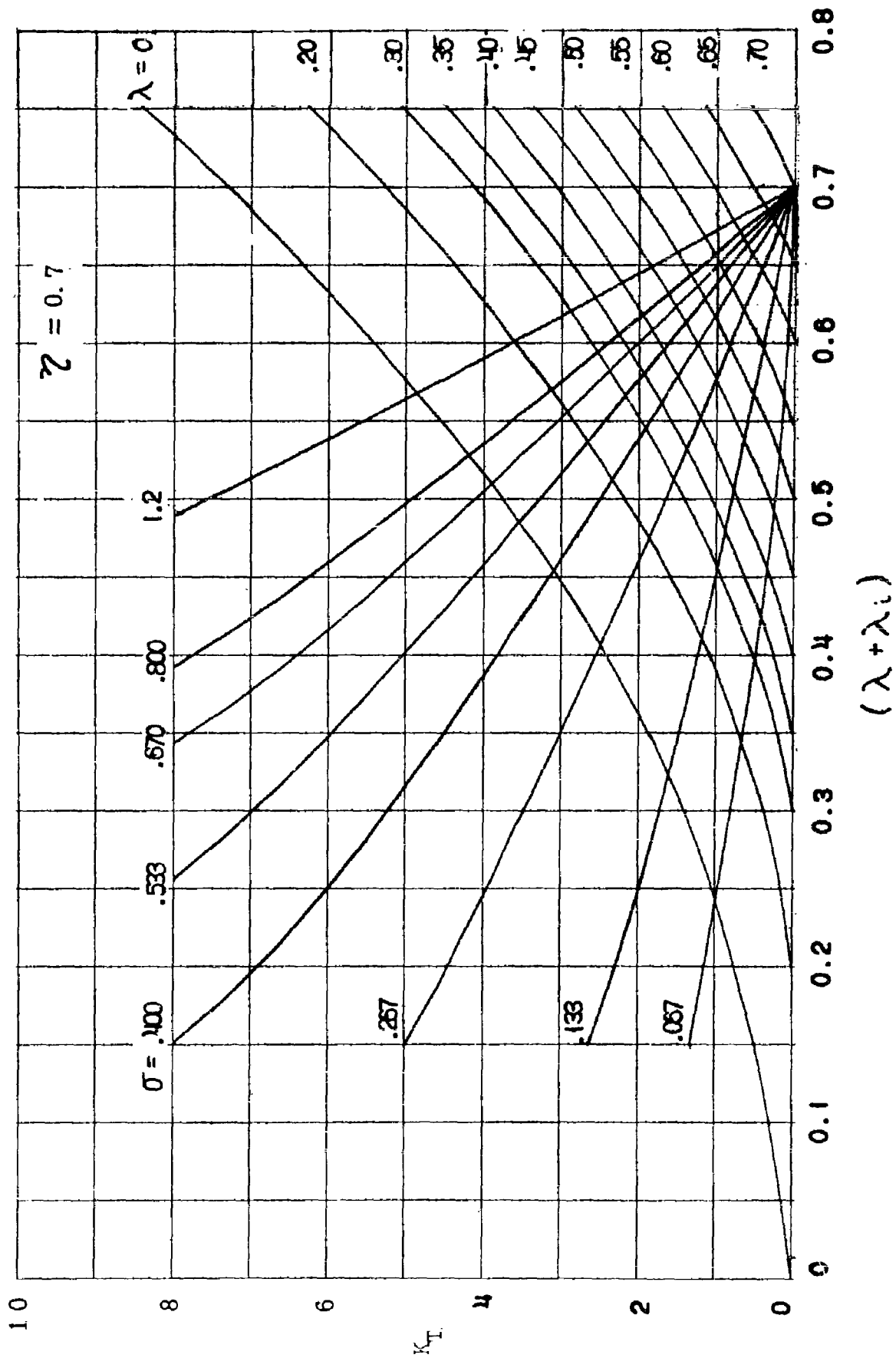
Figure 5 - Thrust Coefficient as a Function of Advance Coefficient and Induced Velocity
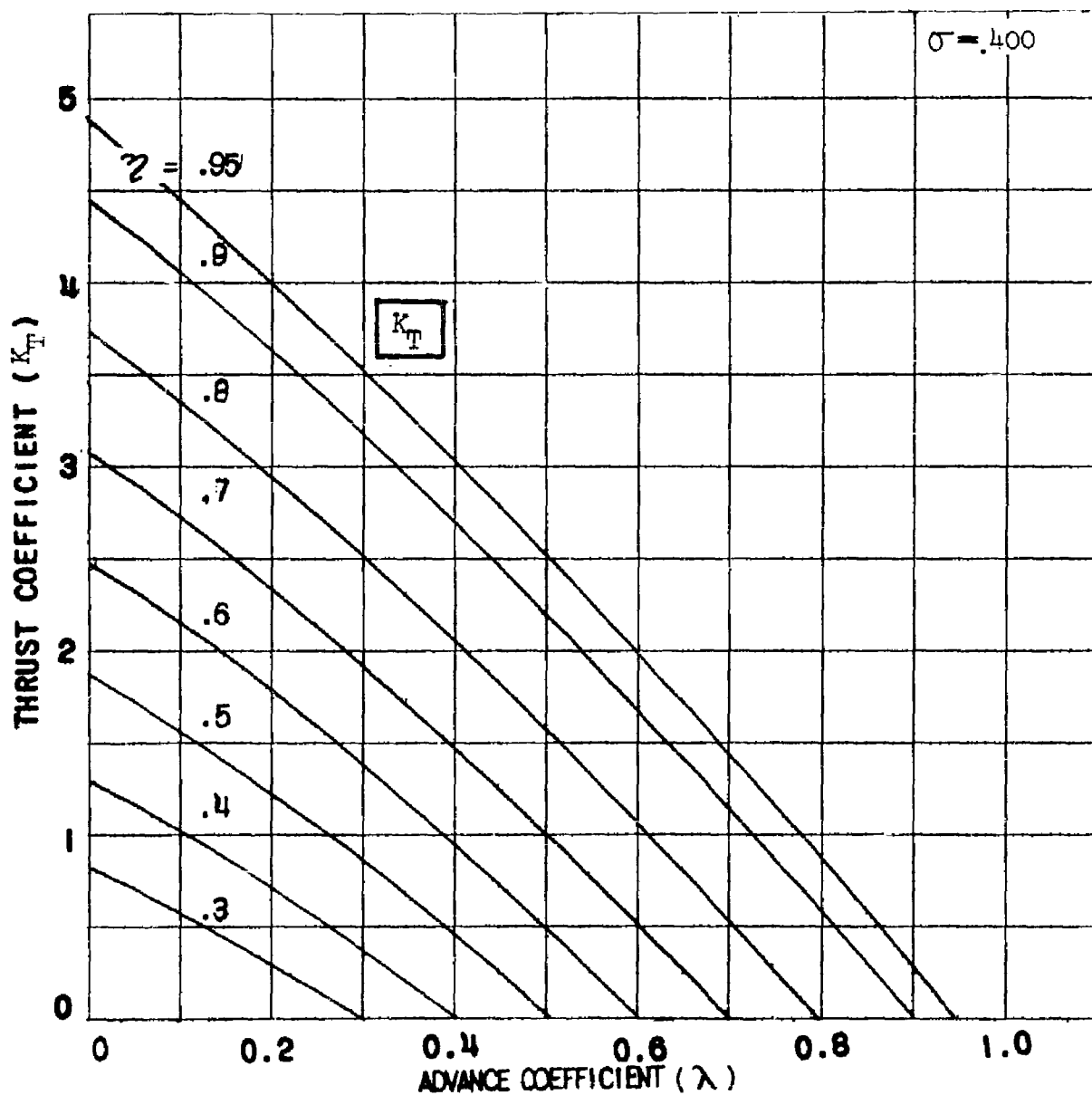Factor for Various Blade Solidities

14
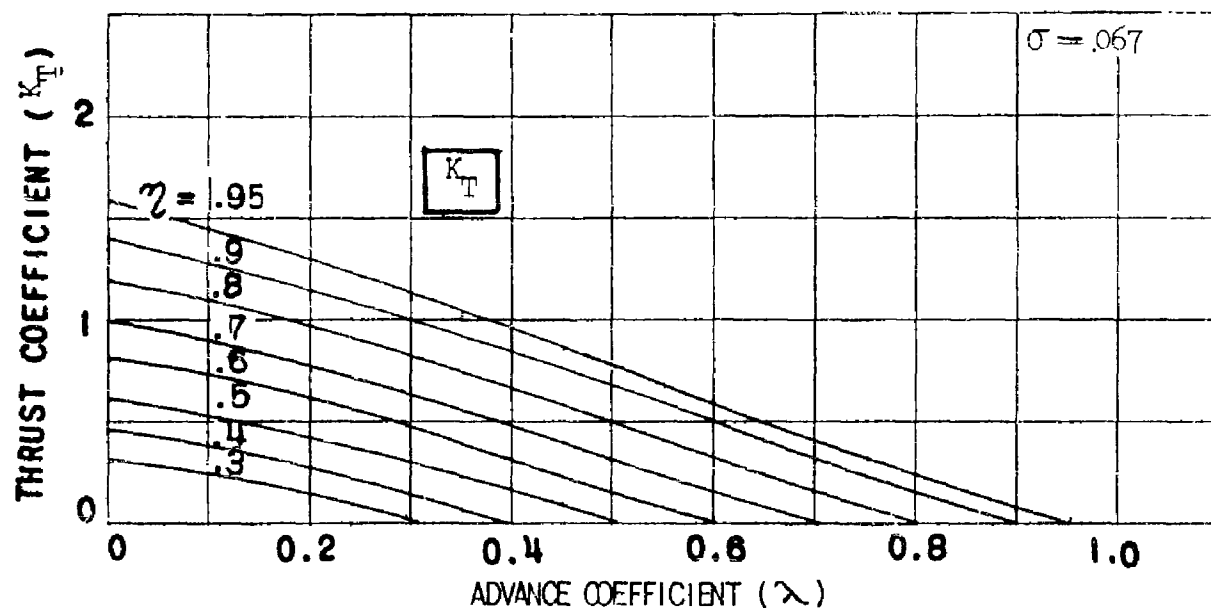
Figure 6(a) - Variation of Thrust Coefficient with Advance Coefficient
and Eccentricity for Various Values of Blade Solidity, σ = .067
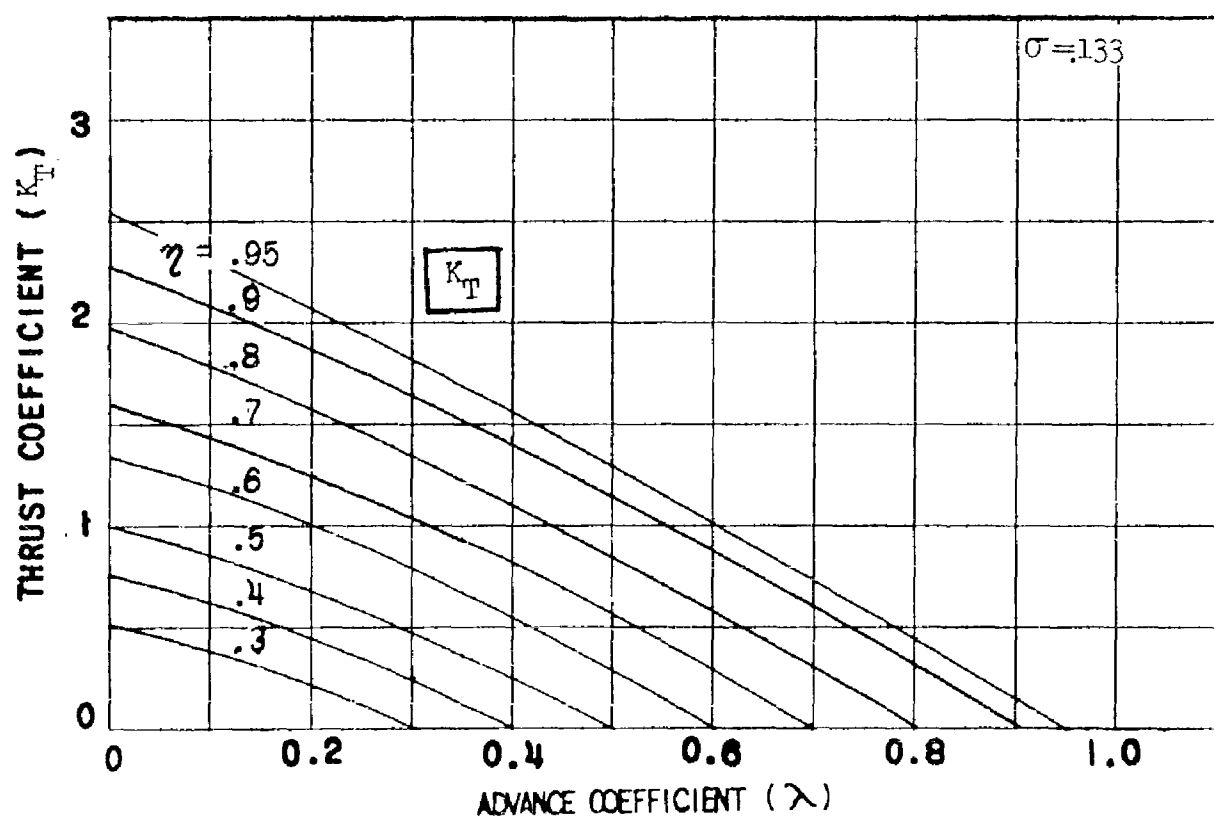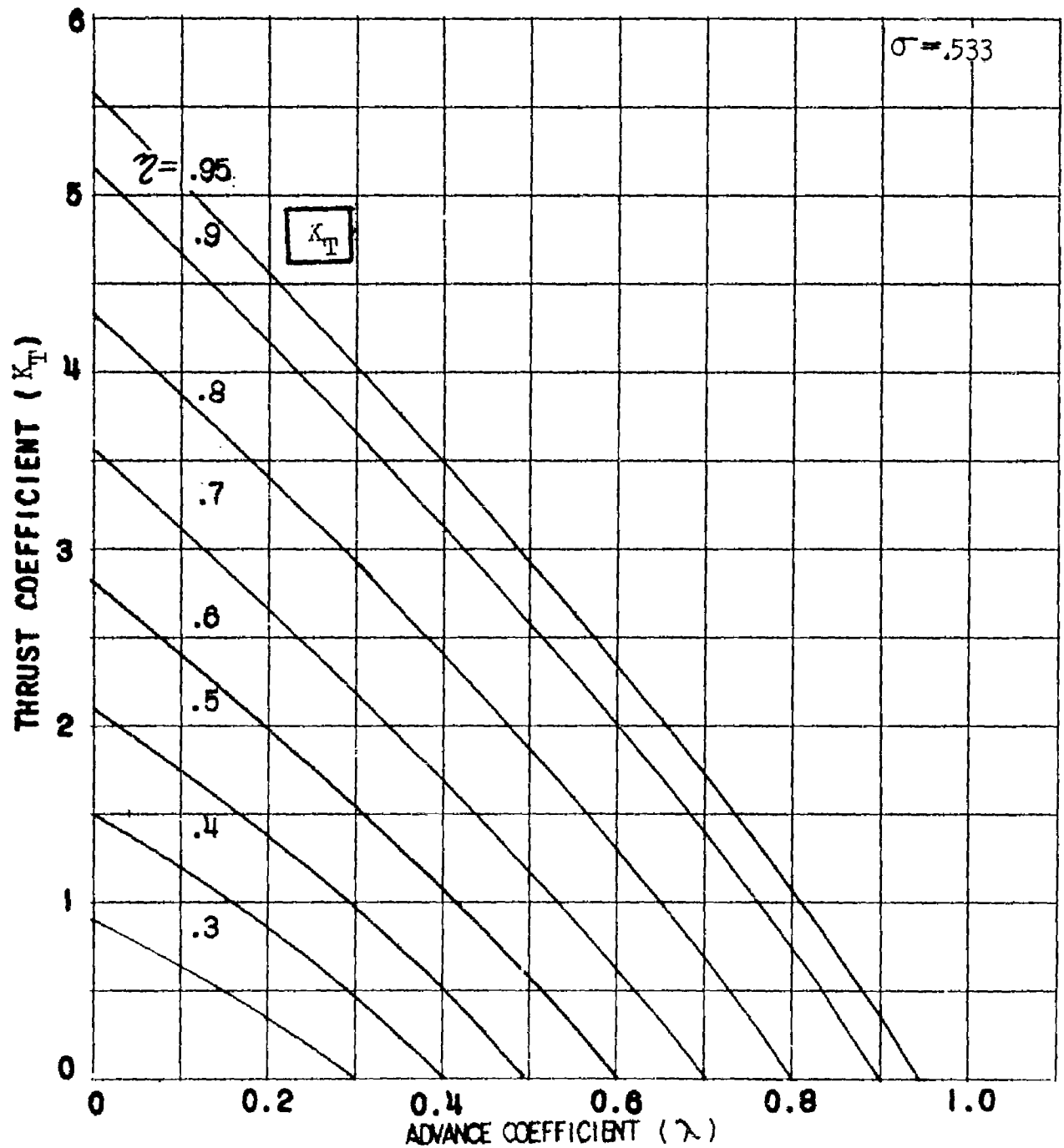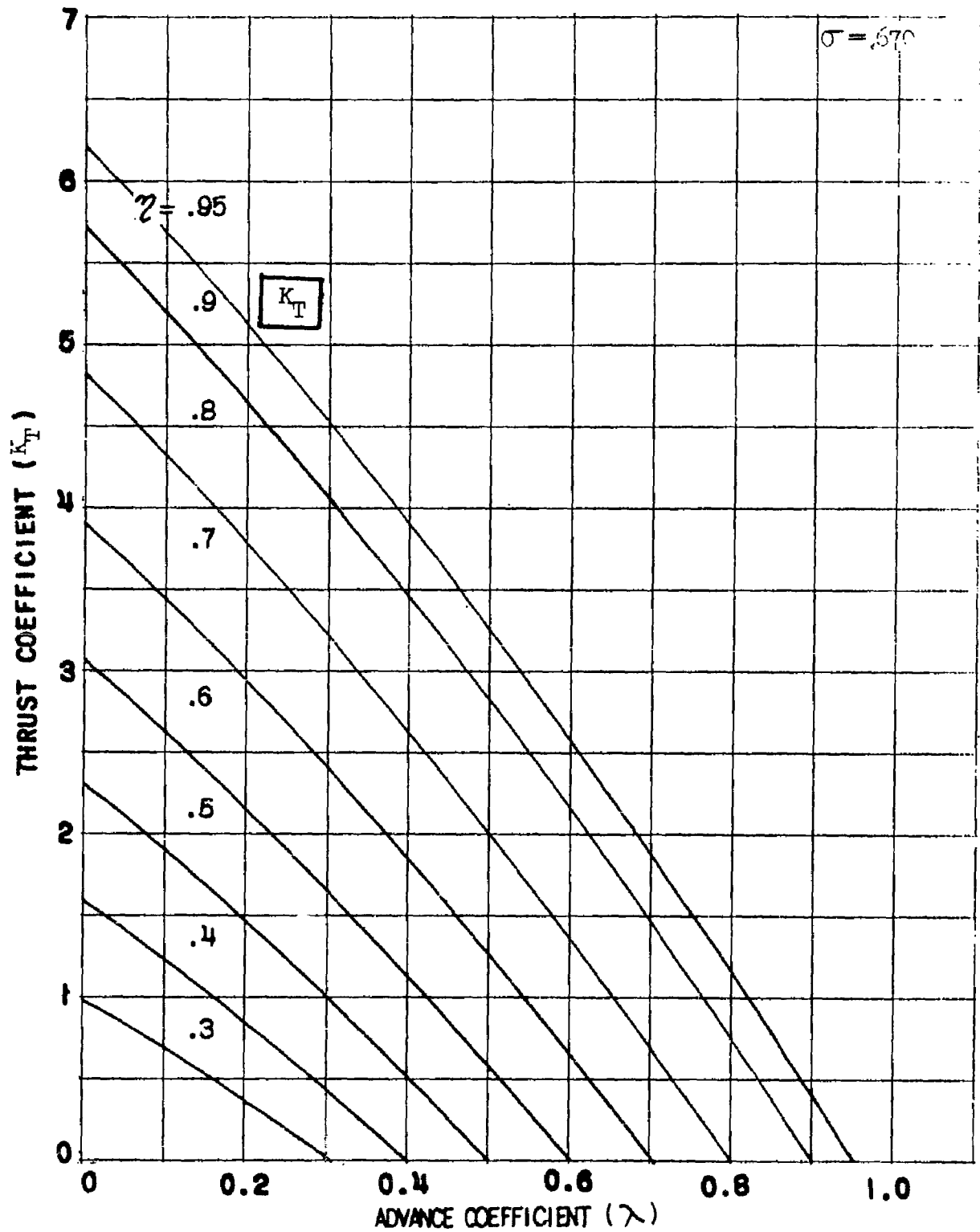

Figure 6(b) - Variation of Thrust Coefficient with Advance Coefficient
and Eccentricity for Various Values of Blade Solidity, σ = .133
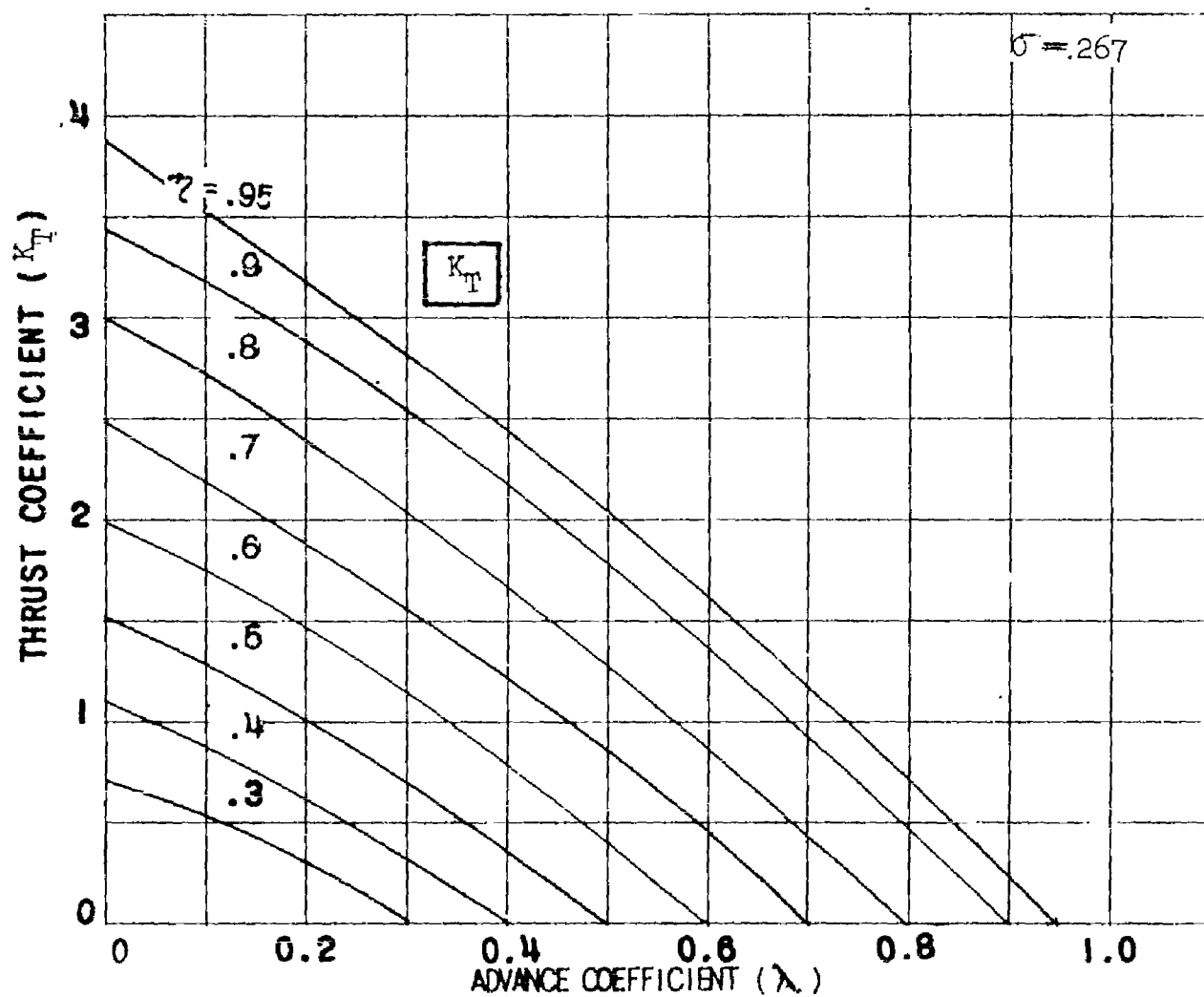
Figure 6(c) — Variation of Thrust Coefficient with Advance Coefficient
and Eccentricity for Various Values of Blade Solidity, σ = .267
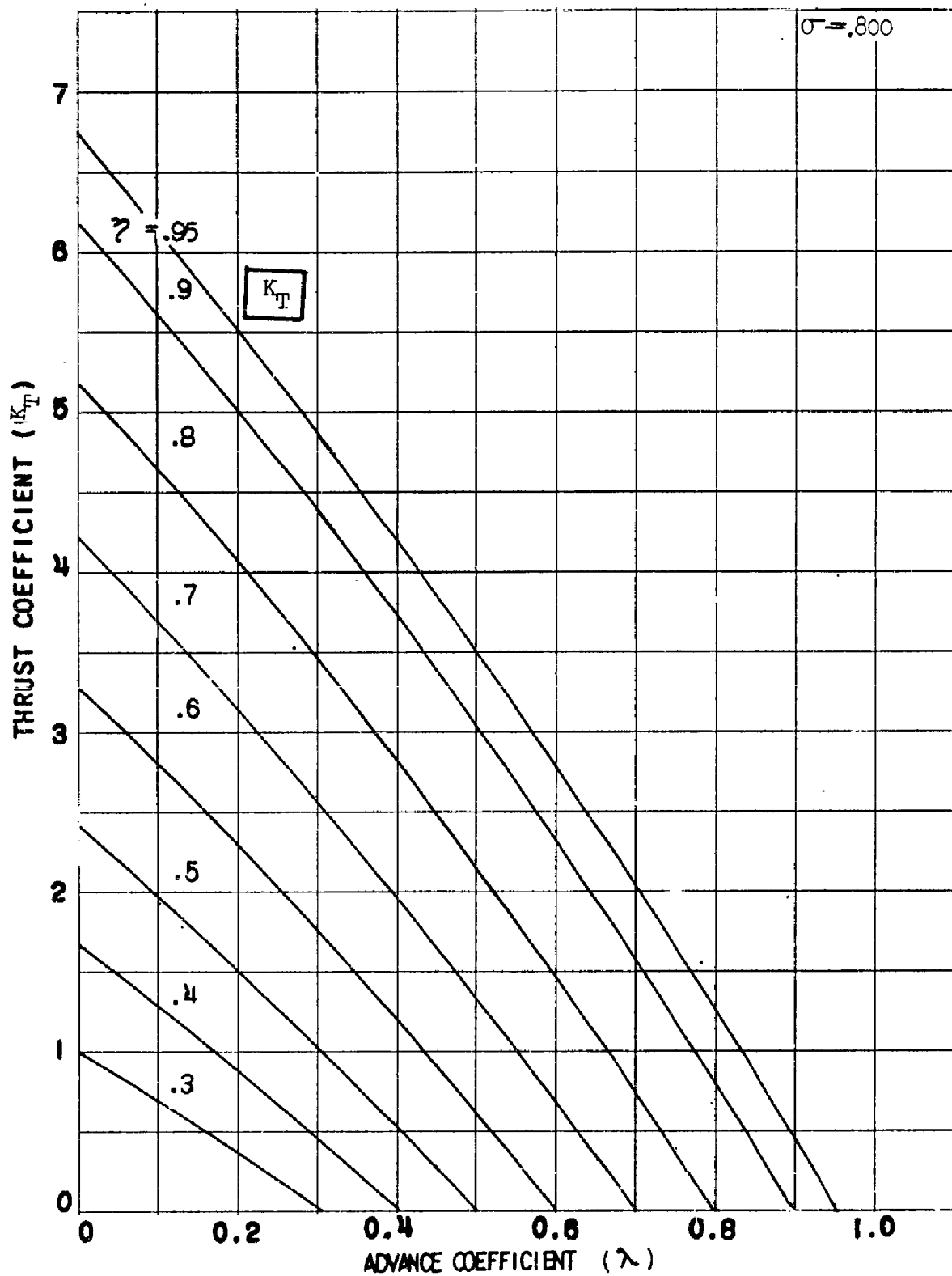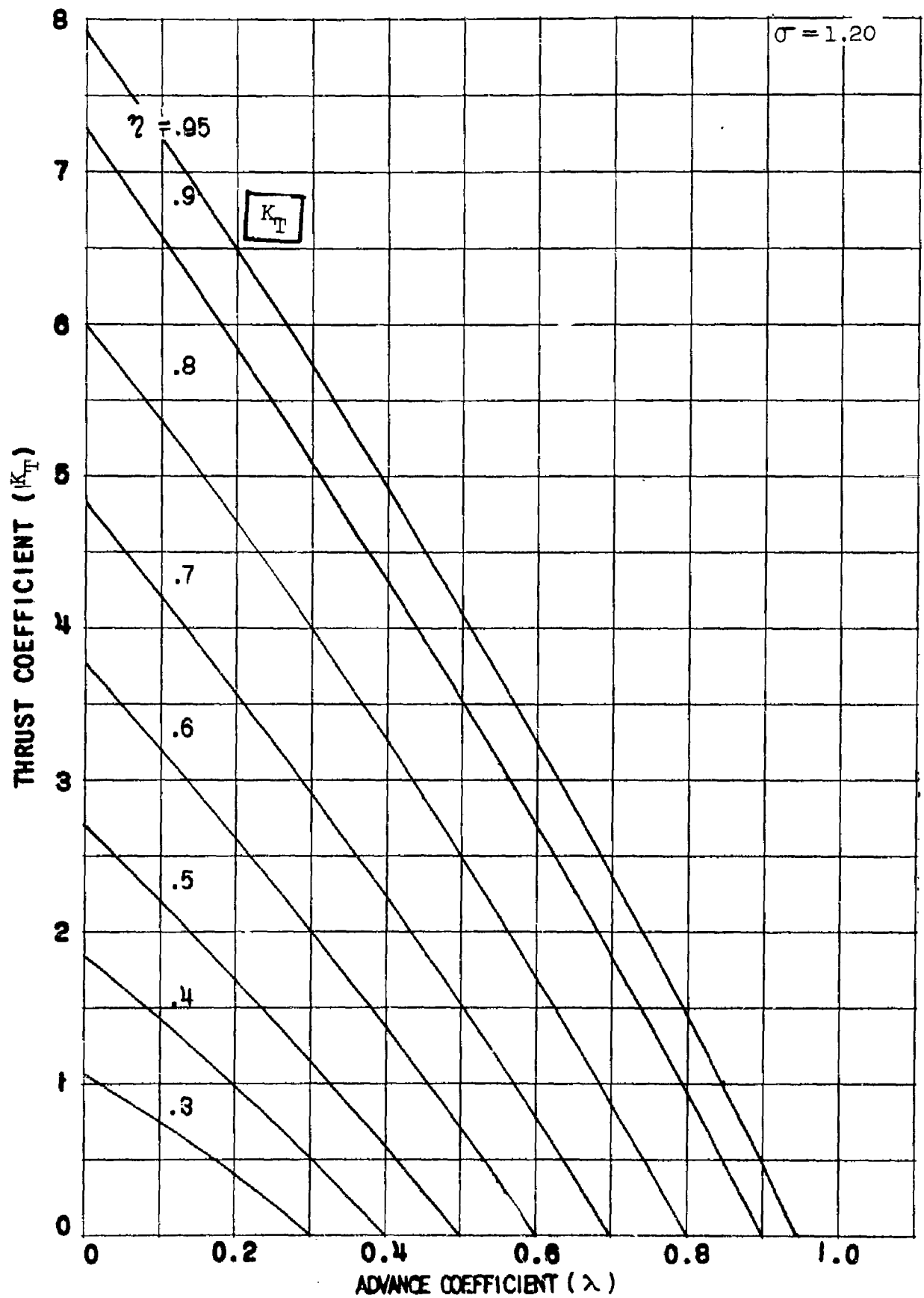
Figure 6(d) – Variation of thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .400$

Figure 6(e) ▲ Variation of Thrust Coefficient with Advance Coefficient
and Eccentricity for Various Values of Blade Solidity, σ = .533

Figure 6(f) - Variation of Thrust Coefficient with Advance Coefficient
and Eccentricity for Various Values of Blade Solidity, $\sigma = .670$

19

Figure 6(g) - Variation of Thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, σ = .800

Figure 6(h) - Variation of Thrust Coefficient with Advance Coefficient
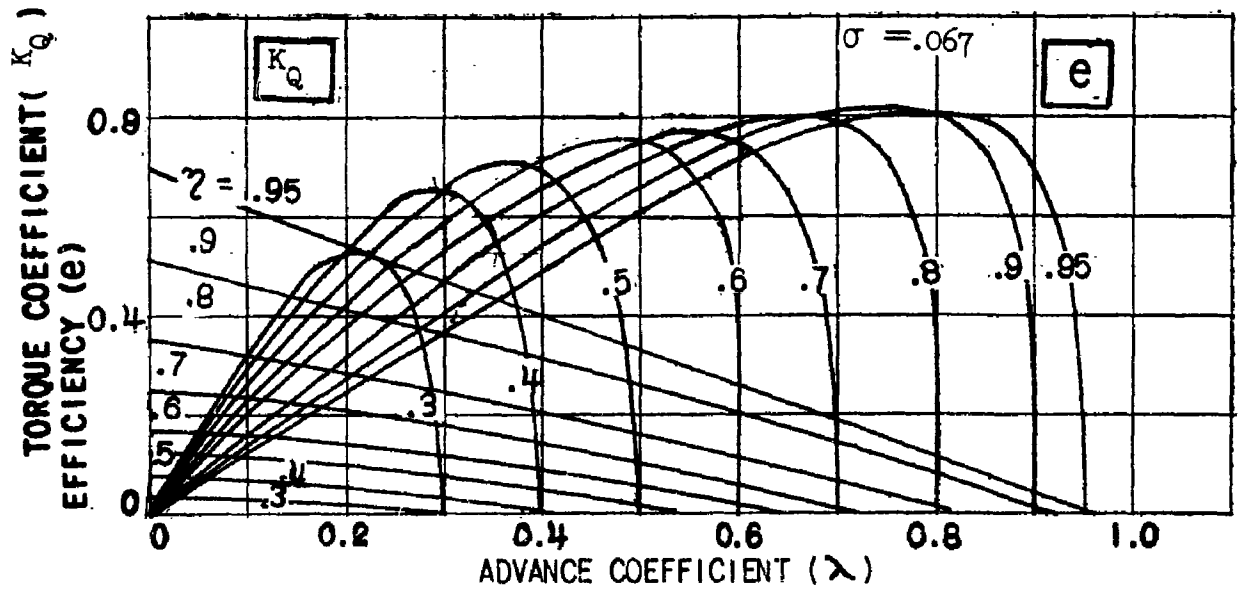and Eccentricity for Various Values of Blade Solidity, σ = 1.200

Figure 7(a) - Variation of Torque Coefficient and Efficiency with Advance
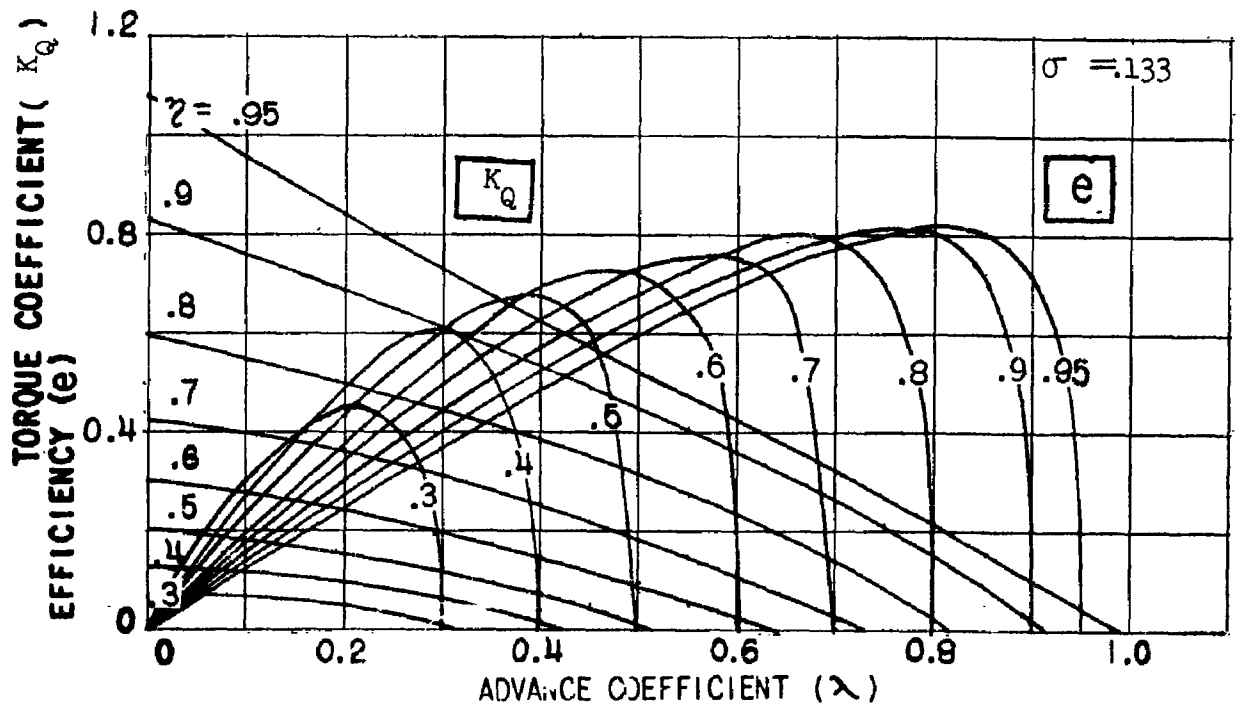Coefficient and Eccentricity for Various Values of Blade
Solidity, σ = .067

Figure 7(b) - Variation of Torque Coefficient and Efficiency with Advance
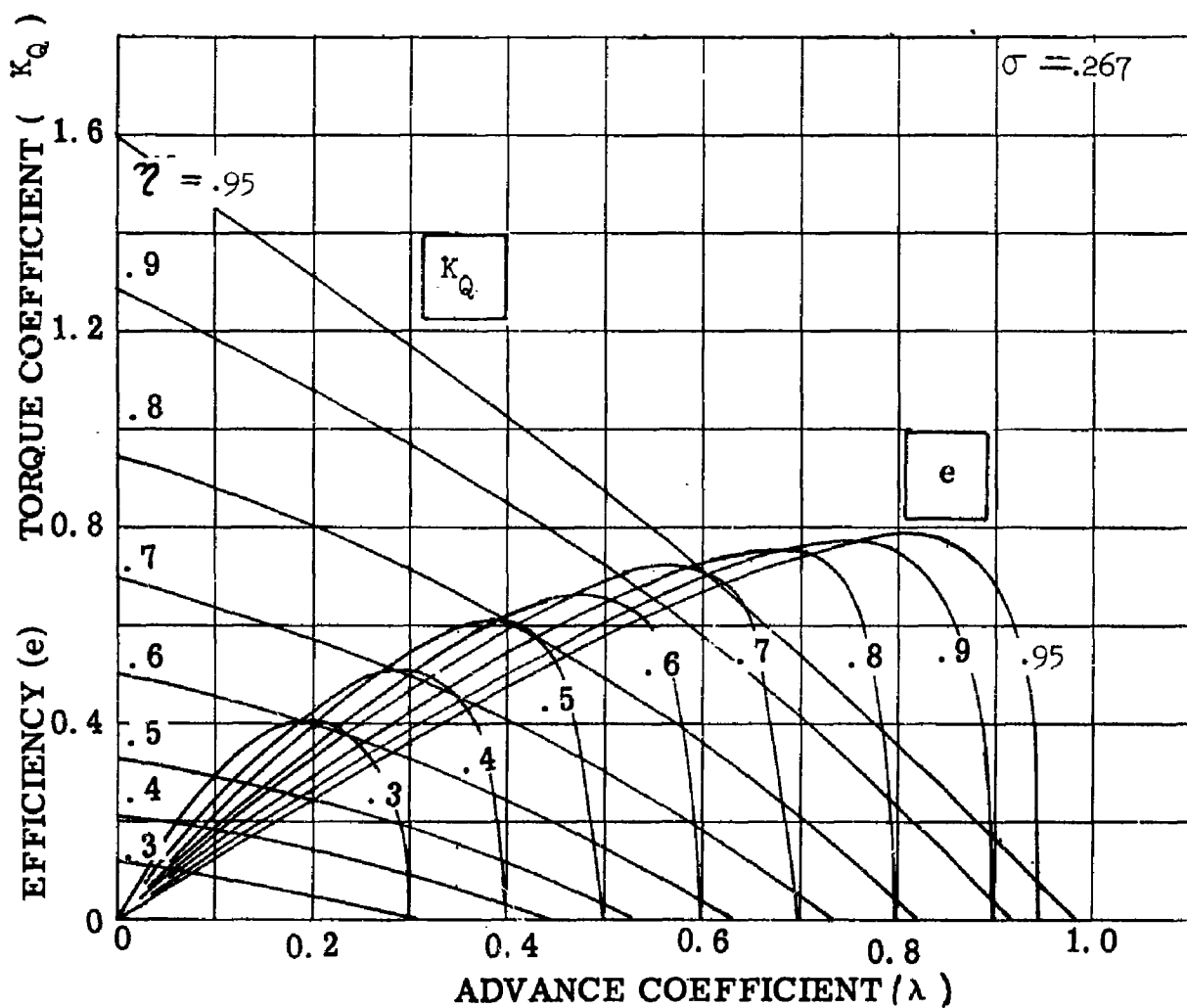Coefficient and Eccentricity for Various Values of Blade
Solidity, σ = .133

22

Figure 7(c) - Variation of Torque Coefficient and Efficiency with Advance
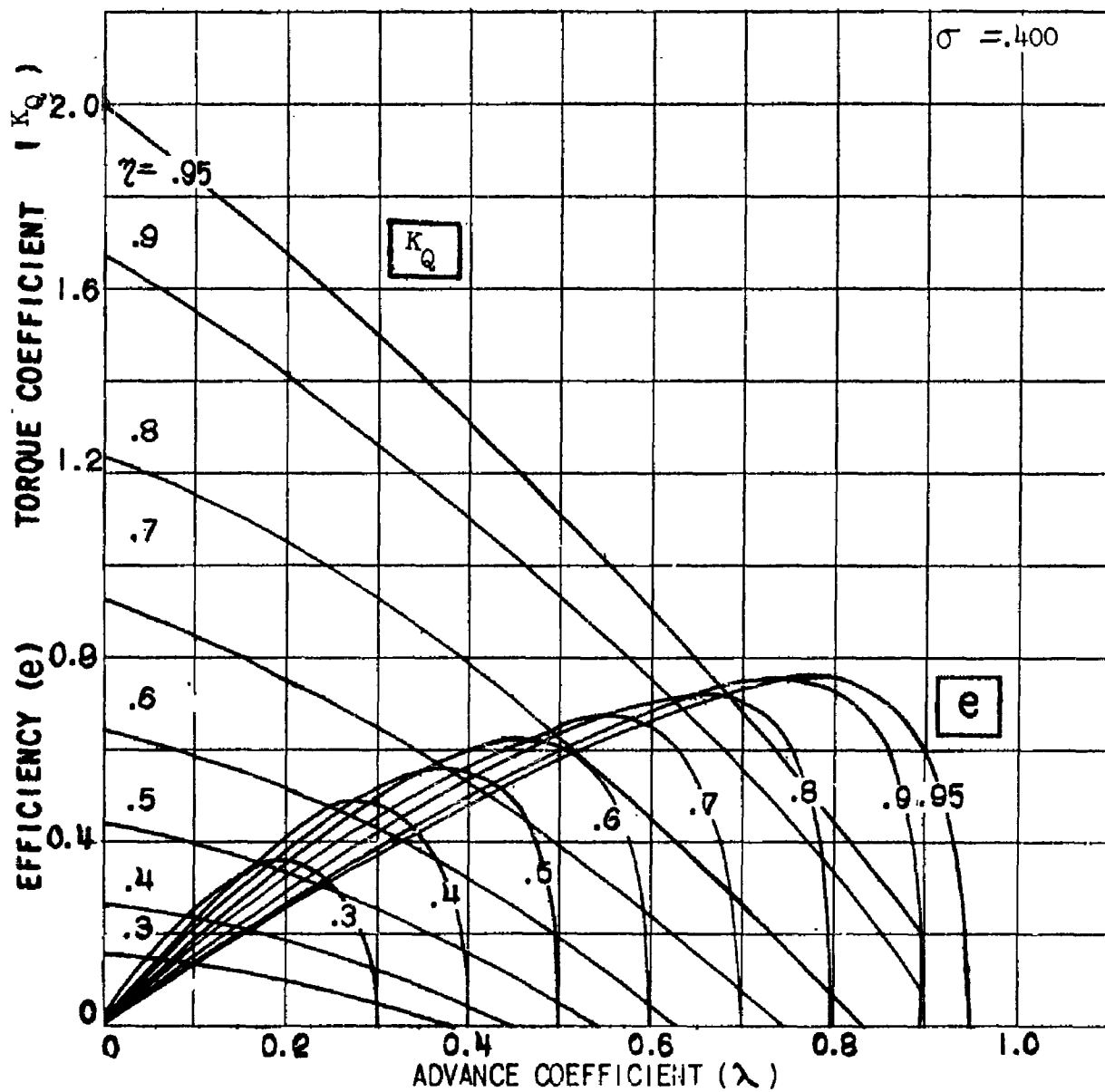Coefficient and Eccentricity for Various Values of Blade
Solidity, σ = .267

Figure 7(d) - Variation of Torque Coefficient and Efficiency with Advance
Coefficient and Eccentricity for Various Values of Blade
Solidity, σ = .400

24

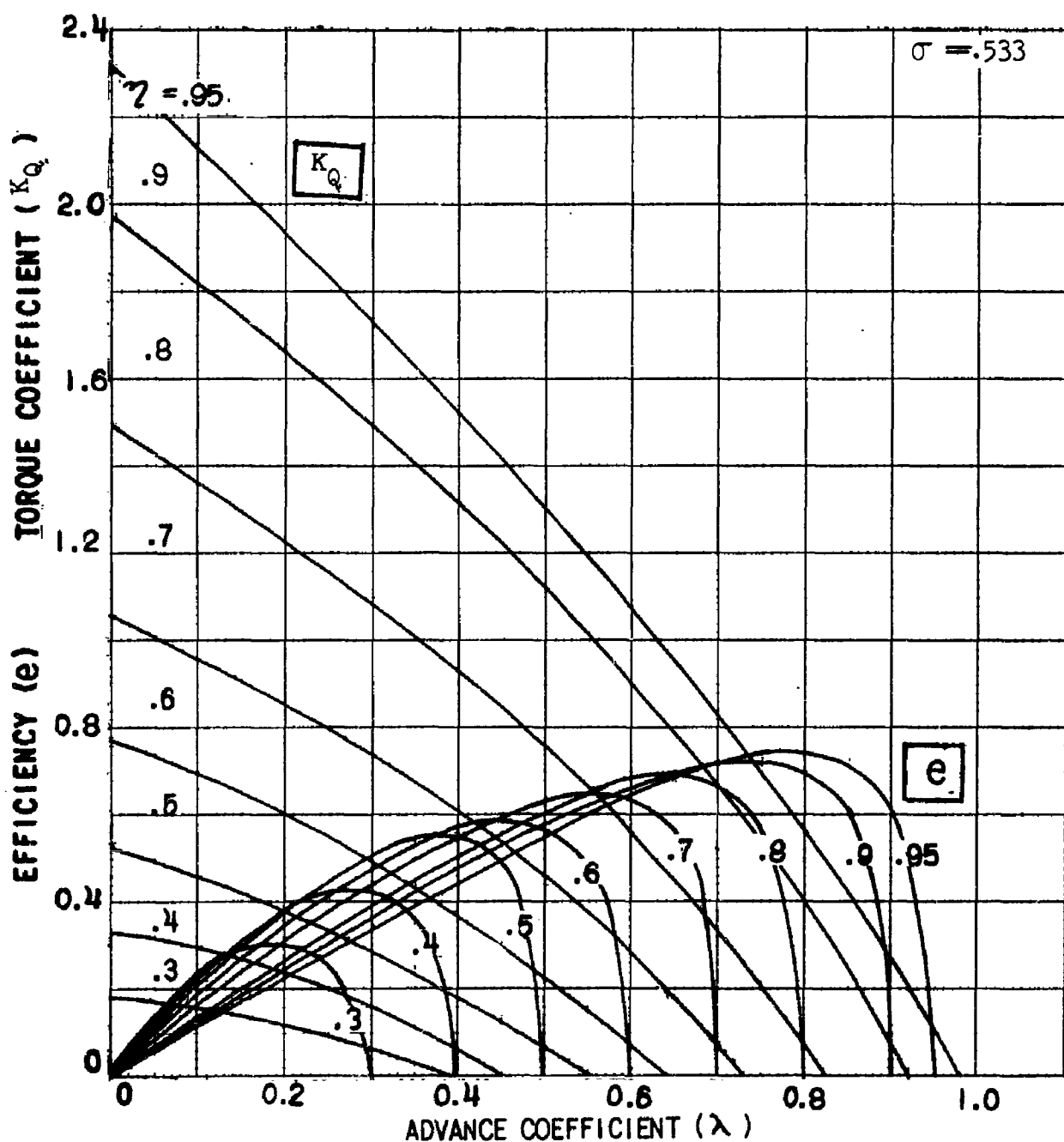Figure 7(ε) - Variation of Torque Coefficient and Efficiency with Advance
Coefficient and Eccentricity for Various Values of Blade
Solidity, σ = .533

25

Figure 7(f) - Variation of Torque Coefficient and Efficiency with Advance
Coefficient and Eccentricity for Various Values of Blade
Solidity, σ = .670

26

Figure 7(g) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, σ = .800
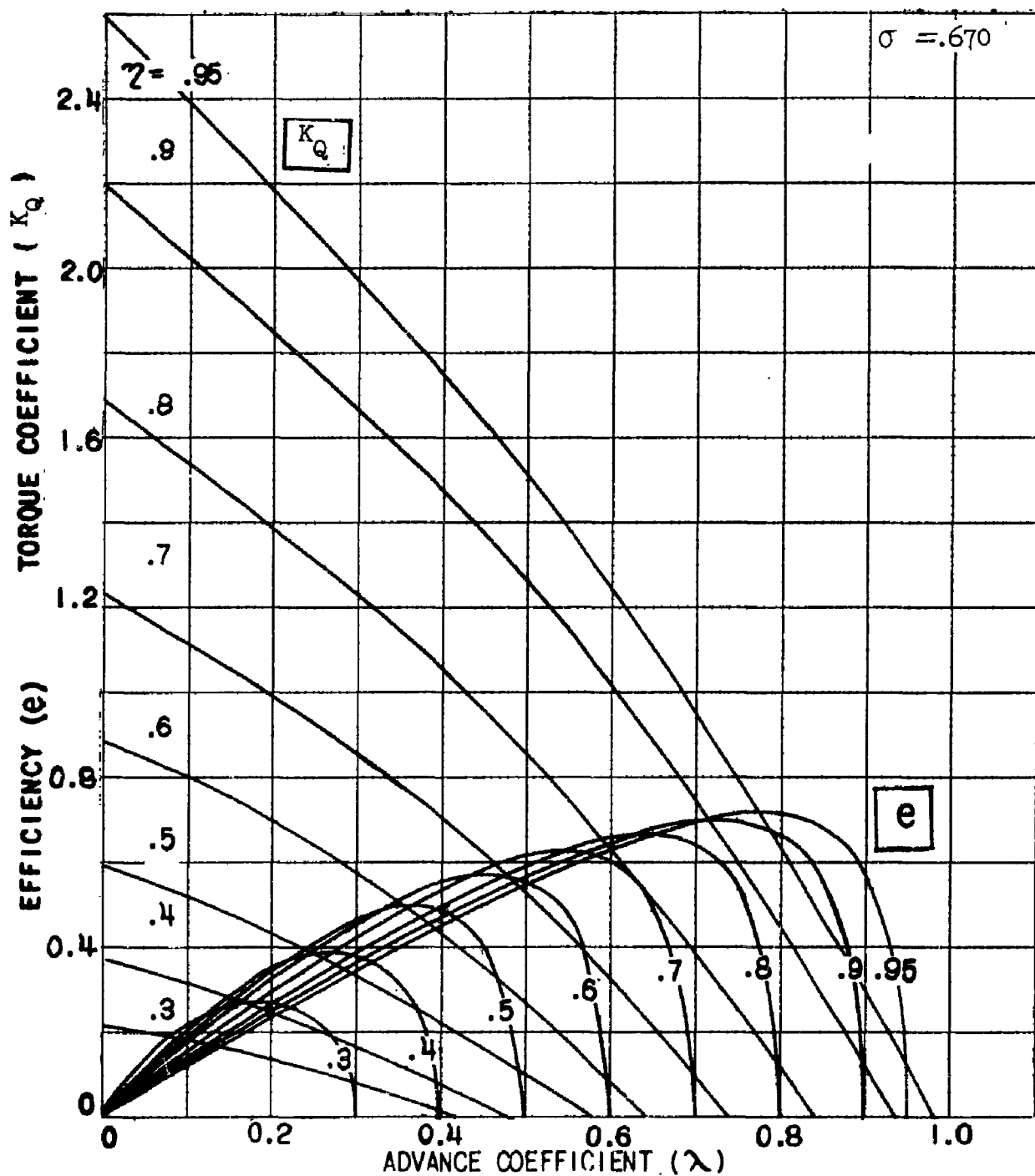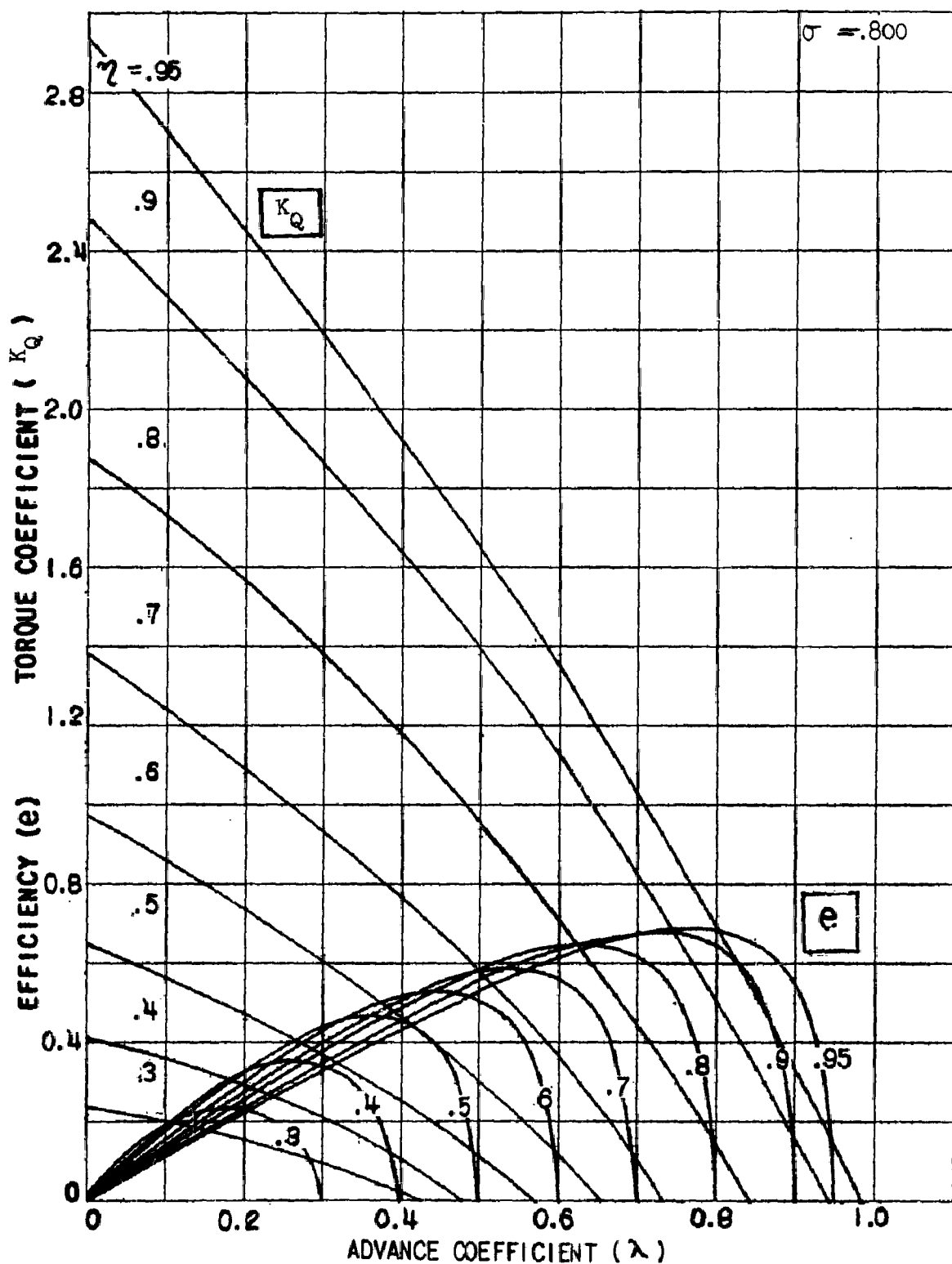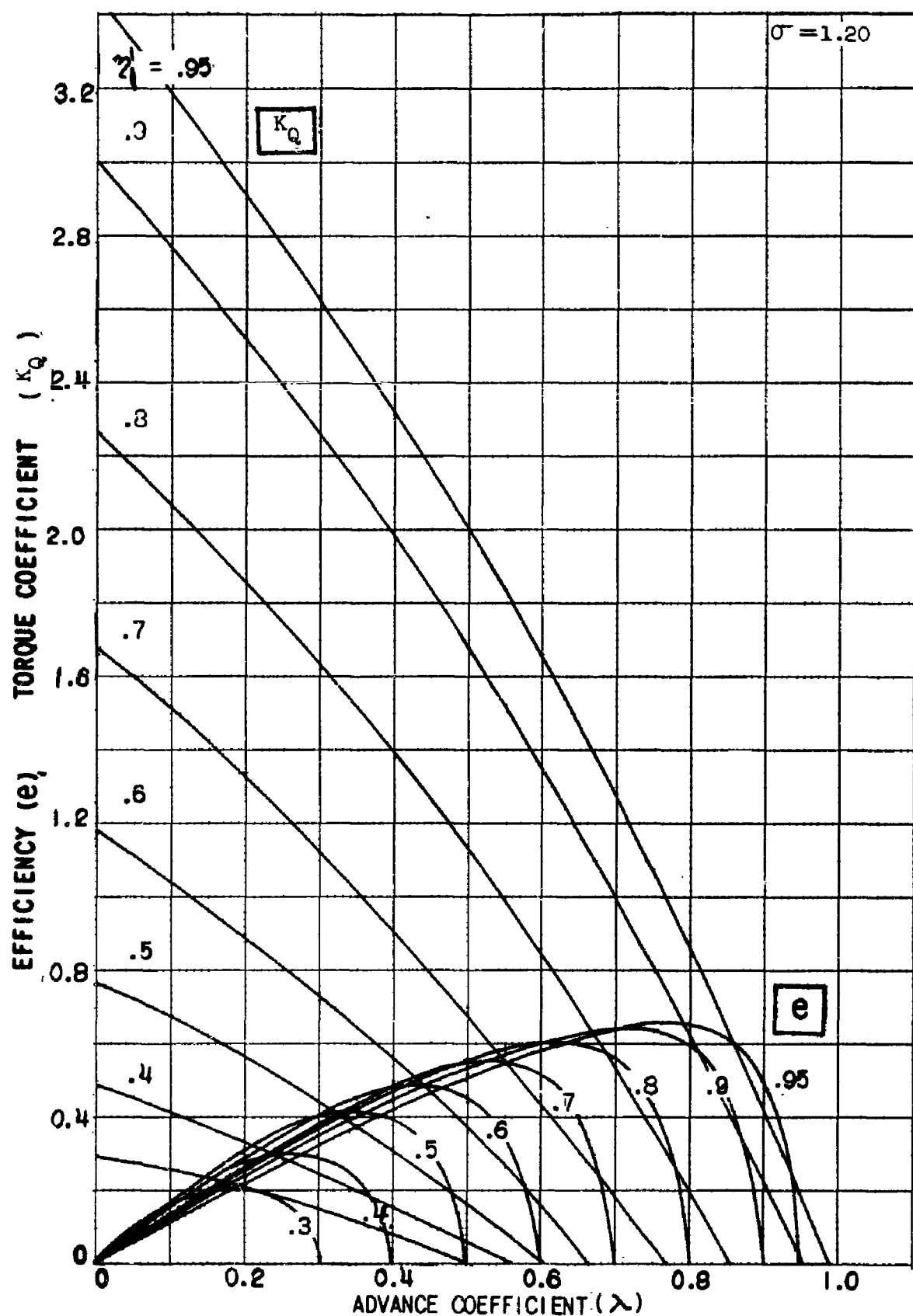
Figure 7(h) - Variation of Torque Coefficient and Efficiency with Advance
Coefficient and Eccentricity for Various Values of Blade
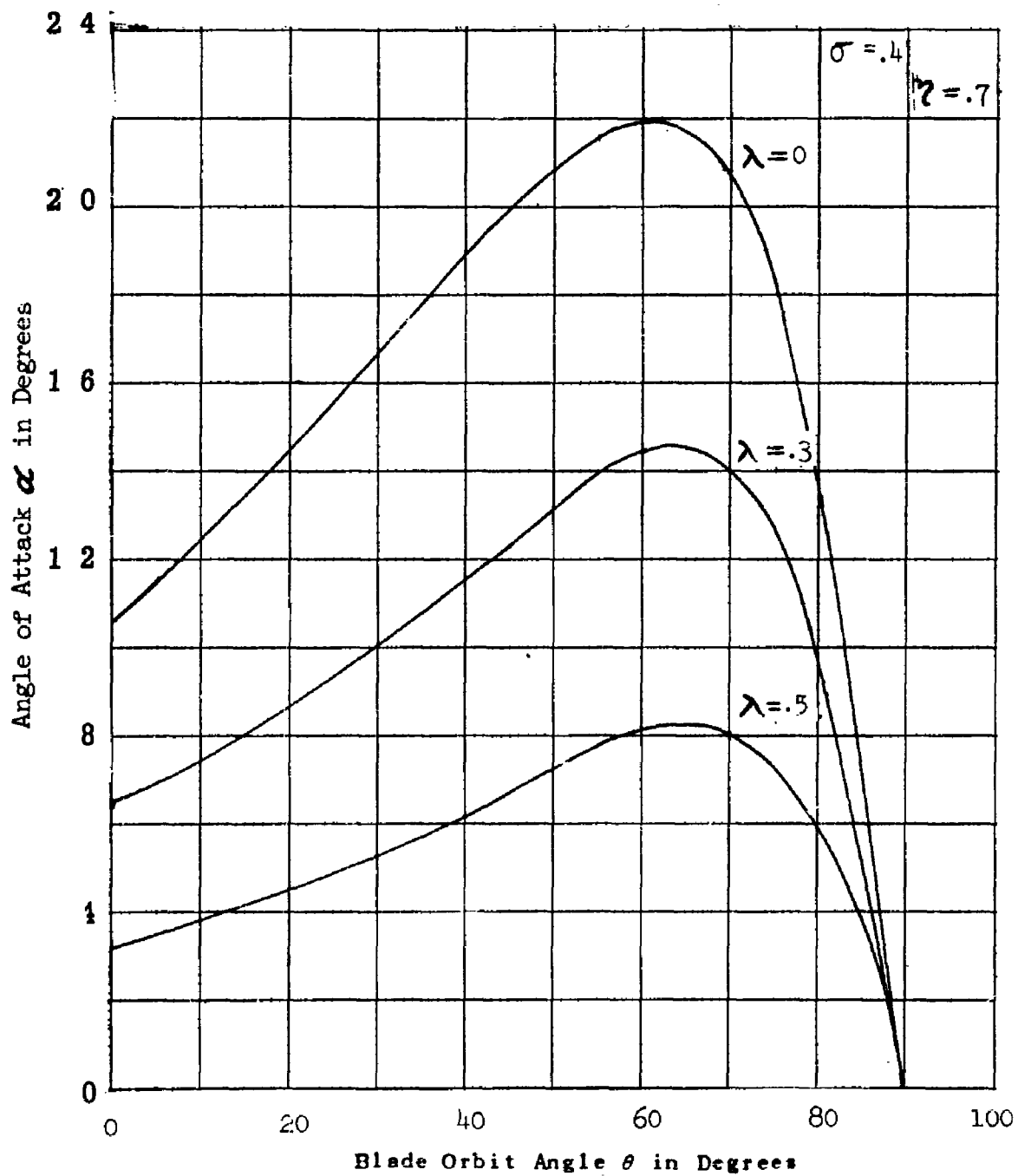Solidity, σ = 1.20

28

Figure 8 - Typical Variation of Angle of Attack of Blade Section with Orbital Position
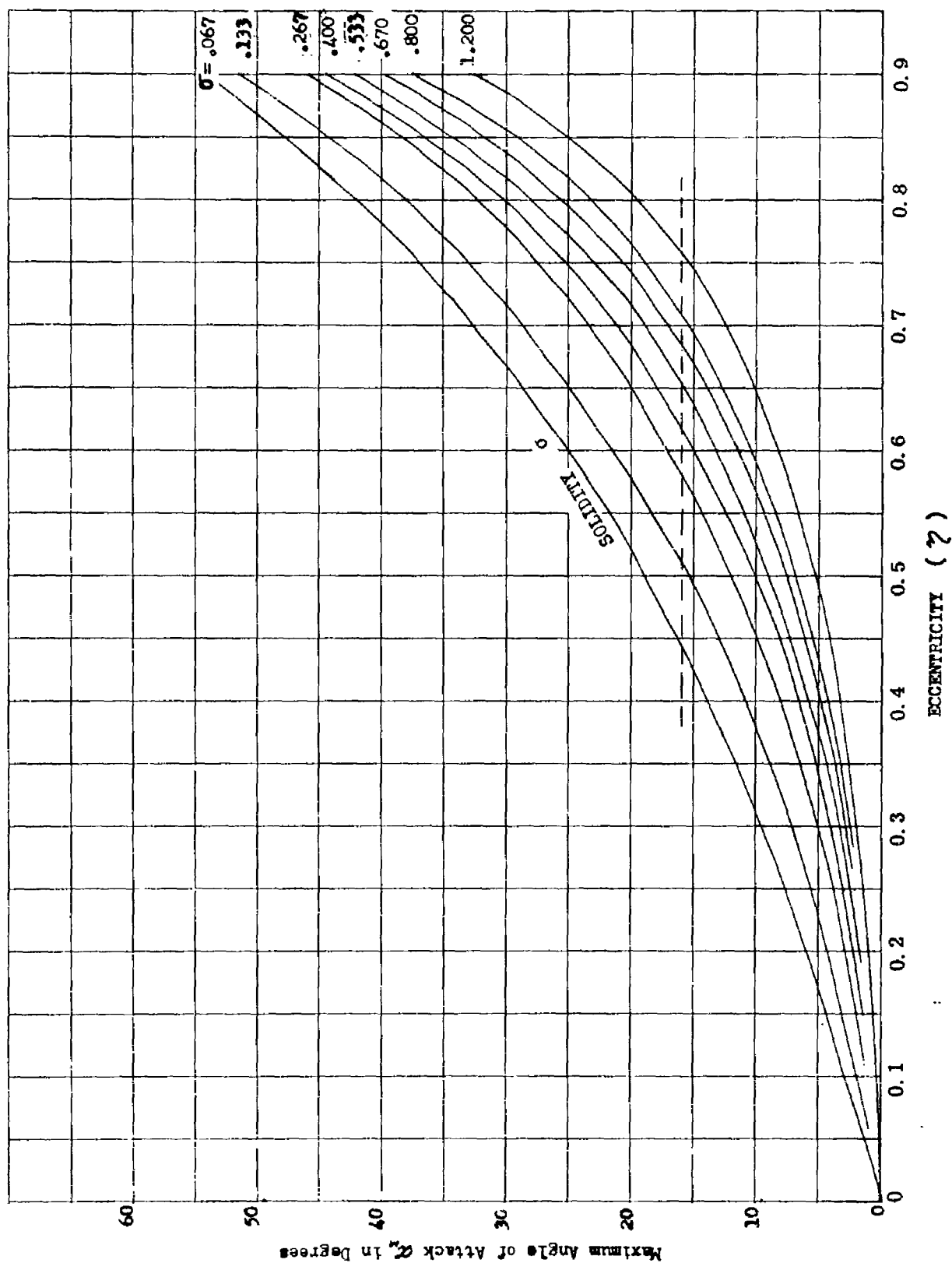
Figure 9 -- Maximum Angle of Attack as Function of Eccentricity and Solidity

Figure 10(a) — Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propeller with Semi-elliptic Blades; Eccentricity = 0.4
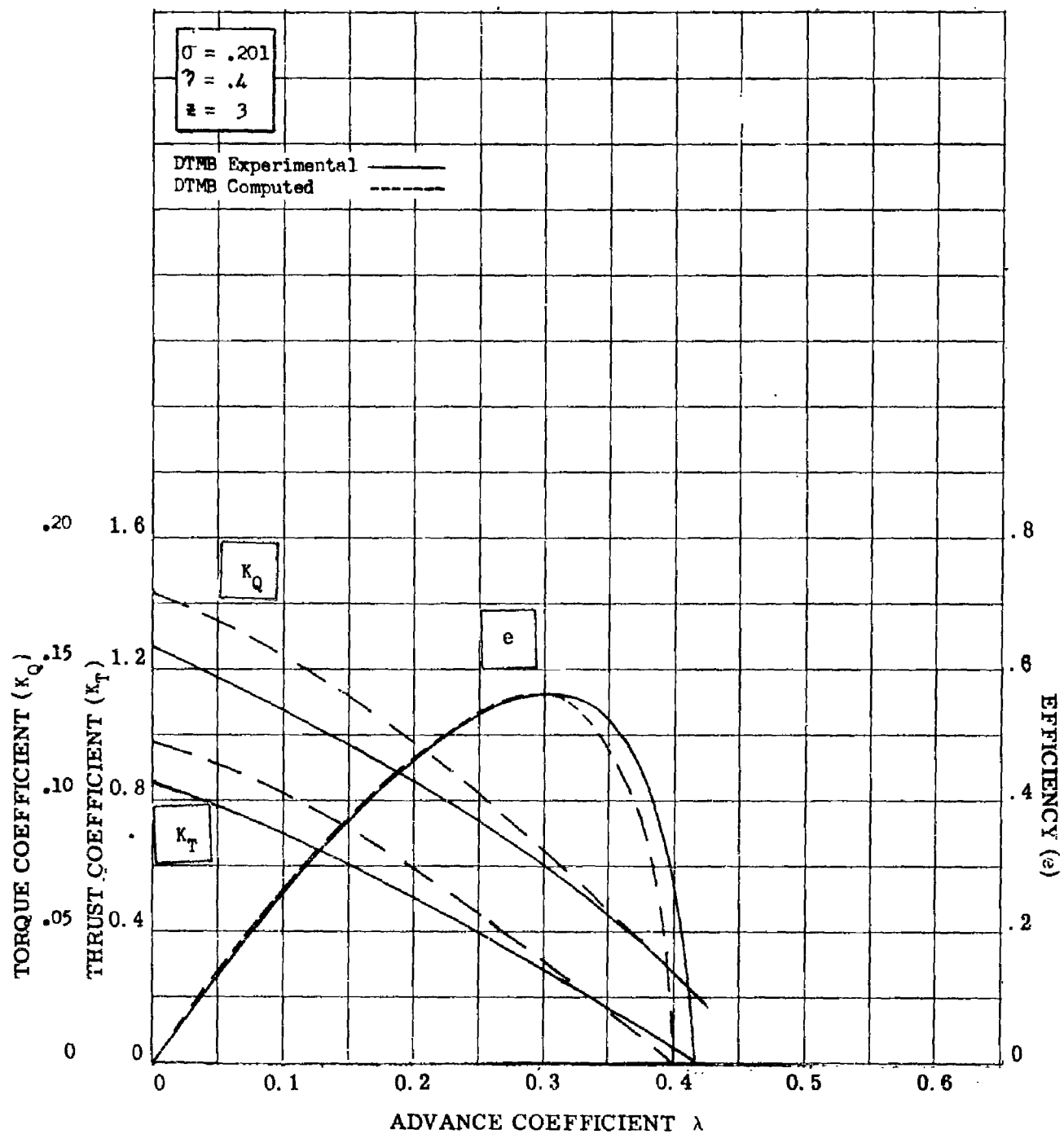
Figure 10(b) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propeller with Semi-elliptic Blades; Eccentricity = 0.4
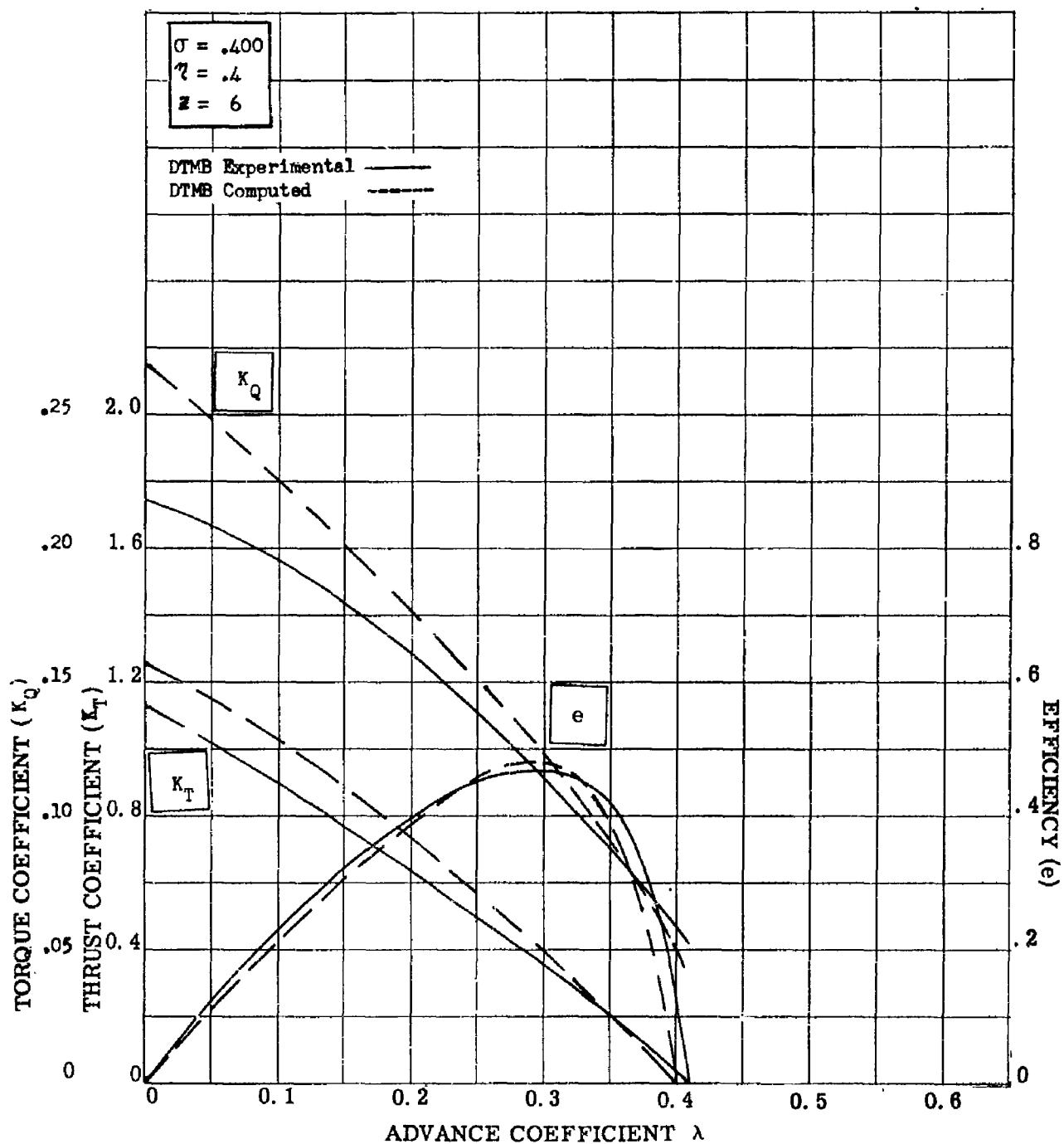
Figure 10(c) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propeller with Semi-elliptic Blades; Eccentricity = 0.4

Figure 11(a) — Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propellers with Semi-elliptic Blades; Eccentricity = 0.6

Figure 11(b) - Comparison of Computed and Experimental Performance Characteristics of a
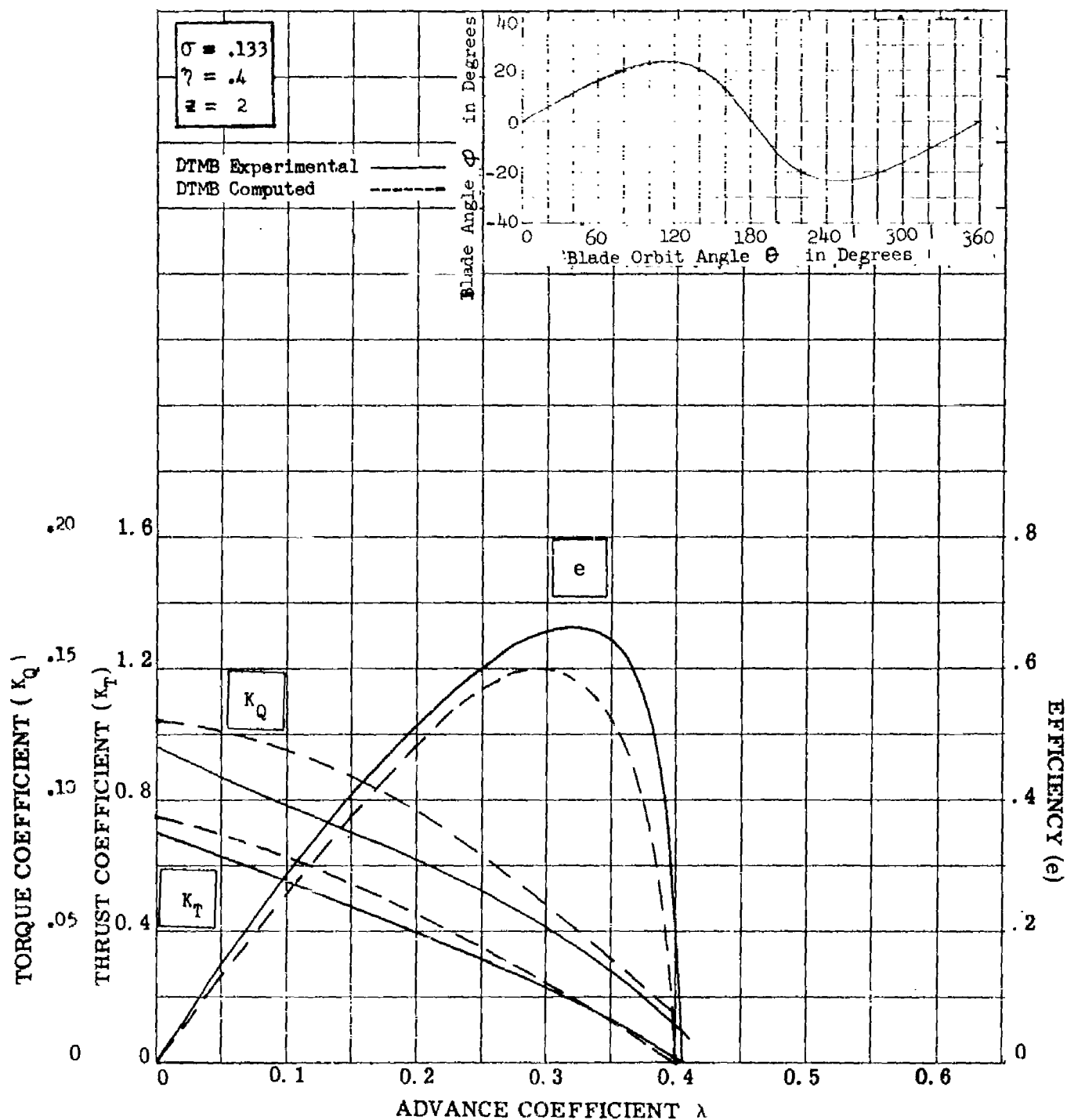Vertical Axis Propellers with Semi-elliptic Blades; Eccentricity = 0.6

Figure 11(c) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propellers with Semi-elliptic Blades; Eccentricity = 0.6
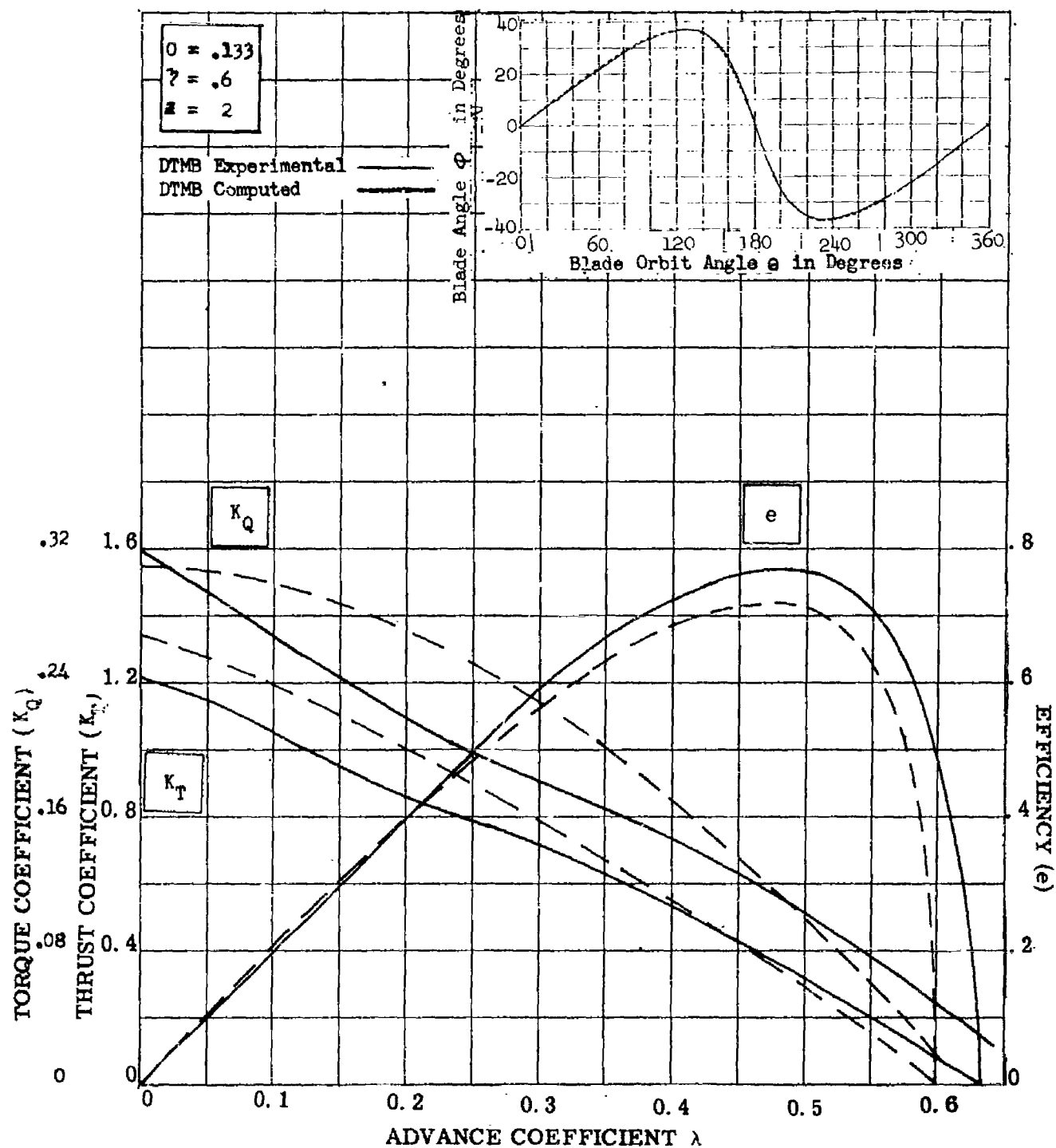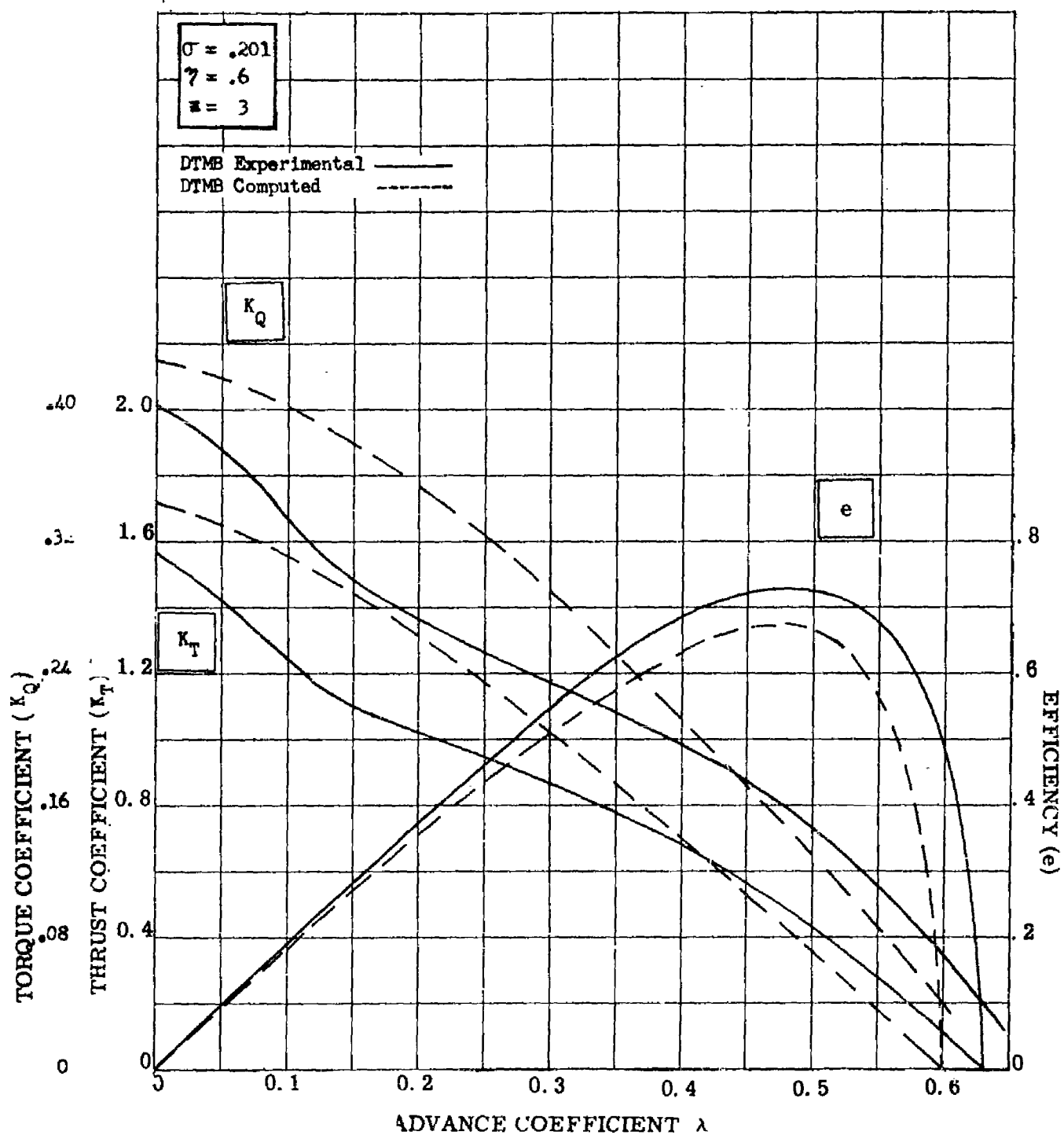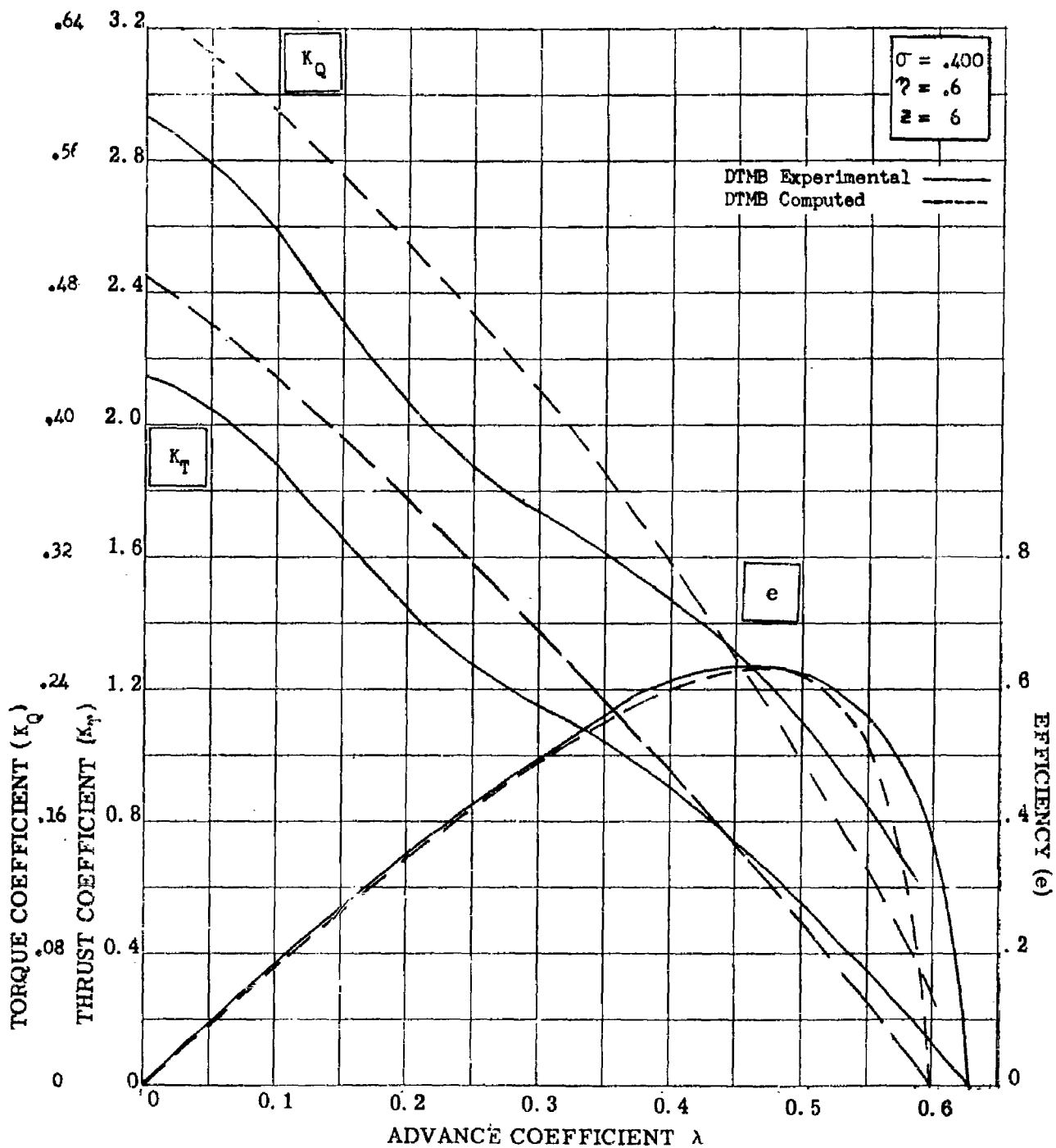
36
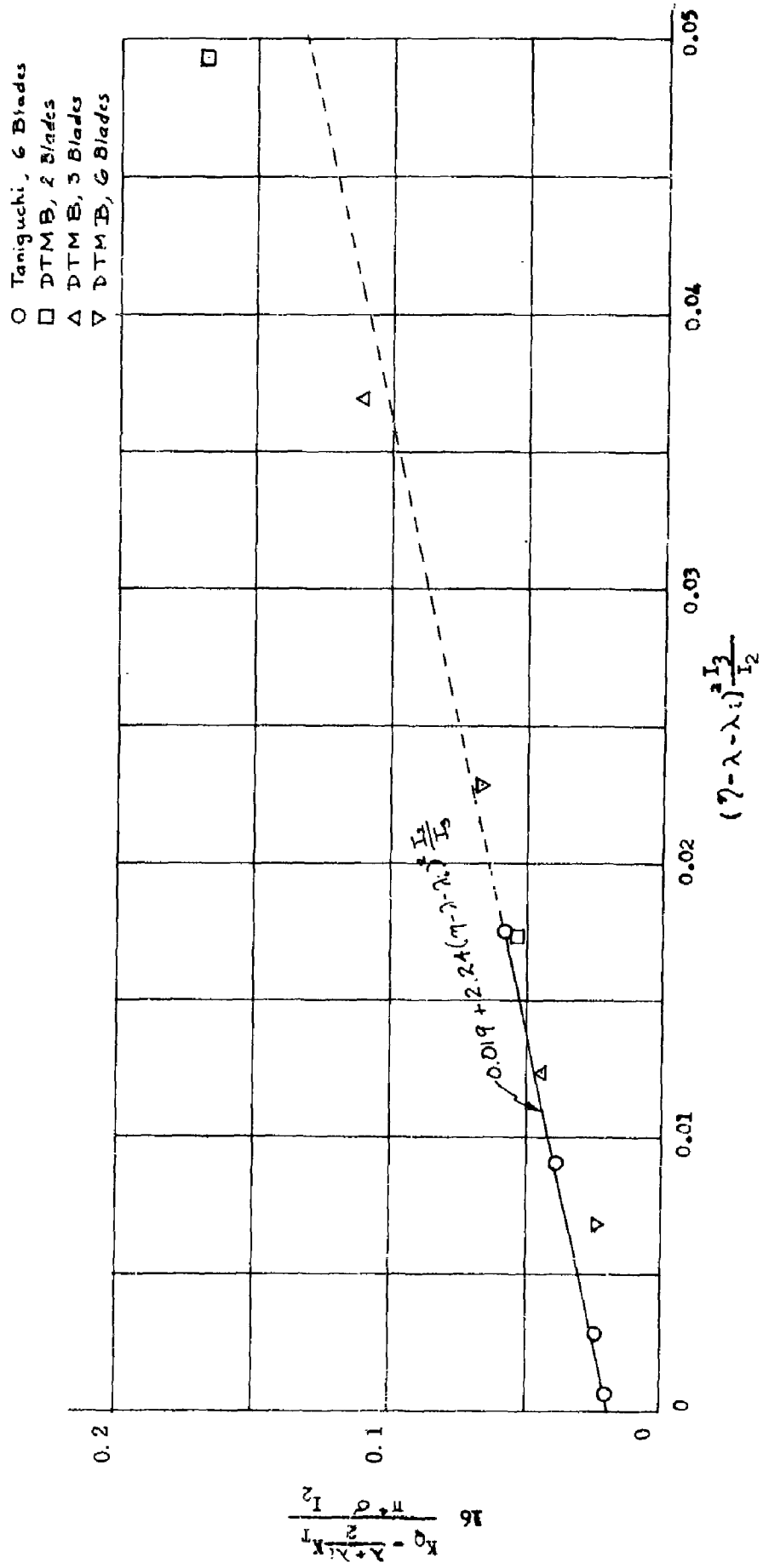
Figure 12 – Plot for Evaluating the Section Drag Coefficient

INITIAL DISTRIBUTION

Copies

7   CHBUSHIPS

    3   Tech Info Br (Code 335)
    1   Prelim Des (Code 420)
    1   Mach Sci & Res (Code 436)
    2   Prop Shafting & Bearing (Code 644)

2   CHONR

    1   Library (Code 740)
    1   Fluid Dynamics Br (Code 438)

1   CDR, USNOTS, Pasadena Annex

10   ASTIA

1   O in C, Transportion Res & Command, Corps of Engineers,
    Fort Eustis, Va.

1   ADMIN, Maritime Adm.

1   HD, Dept NAME, MIT

1   DIR, ORL, Penn State

1   HD, Dept of NAME, Univ of Mich

1   DIR, Davidson Lab, SIT

1   SNAME, 74 Trinity Place, New York 6, New York, Attention Librarian

1   Applied Mechanics Reviews, 8500 Culebra Road, San Antonio 6, Texas

1   George G. Sharp Inc., New York

1   Gibbs and Cox, Inc., New York

1   Electric Boat Division, General Dynamics Corp., Groton, Conn.

1   NNS & DD Co.

1   Hydronautics, Inc., 200 Monroe Street, Rockville, Md.

1   SUPT, Ship Div., Natl Phys Lab, Teddington Middlesex, England

1   DIR, Nederlandsch Scheepsbouwkundig Proefstation, Wageningen,
    The Netherlands

1   HD, Dept of Naval Arch, Univ of Naples, Naples, Italy

1   Dr. Eng. T. Izubuchi, Secretary, Shipbuilding Research Assoc. of Japan, Tokyo, Japan

1   Dr. K. Taniguchi, Experimental Tank, Mitsubishi Shipbuilding Eng.Co., 712 Syowa, Nagasaki, Japan

1   DIR, Skipsmodeltanken, Trondheim, Norway

1   DIR, Statens Skeppsprovninganstalt, Goteborg, Sweden

1   DIR, Hydro and Aerodynamics Lab, Hjortekaersvej 99, Lyngby, Denmark

1   RADM Roger E. Brard, Drecteur, Bassin d' Essais des Carenes, 6 Boulevard Victor, Paris (XVe) France

1   Dr. L. Malavard, Officer National d'Etudes et de Recherches Aeronautiques, 25 Avenue de la Division – Le Clerc, Chatillon, Paris, France

1   Gen. Ing. U. Pugliese, Presidente, Institute Nazionale per Studi ed Esperienze di Architetture Navale, Via Della Vasca Navale 89, Rome, Italy

1   Dr. M. Acevedo y Campoanor, Director, Canal de Experiencias Hidrodinamicas, El Pardo, Madrid, Spain

1   Dr. J. Dieudonne, Directeur, Institute de Recherches de la Construction Navale, 1 Boulevard Haussmann, Paris (90), France

1   Dr. S.L. Smith, Director, British Shipbuilding Research Association, Prince Consort House, 27/29 Albert Embankment, London, S.E. 11, England

1   Dr. H.W.E. Lerbs, Director, Hamburg Model Basin

1   Prof. Laurens Troost, Jr., Chairman, National Council for Industrial Research, TNO, 12 Koningskade, P.O. Box 294, The Hague, Netherlands

8   ALUSNA London

David Taylor Model Basin. Report 1564.
PERFORMANCE OF VERTICAL AXIS (CYCLOIDAL) PRO-
PELLERS CALCULATED BY TANIGUCHI'S METHOD, by
W.L. Haberman and E.E. Harley. Nov 1961. iv, 39p. illus.,
graphs, refs.   UNCLASSIFIED

A method proposed by Taniguchi has been used to compute the
performance characteristics of vertical axis propellers having
cycloidal blade motion and semi-elliptic blades. Numerical re-
sults of thrust and torque coefficient and efficiency are presented
for a wide range of advance coefficients, maximum blade angle,
and blade solidity.
Good agreement between the experimental performance and the
computed results is obtained for two, three, and six-bladed
cycloidal propellers.

1. Cycloidal propellers--
   Performance--Analysis
   I. Haberman, W.L.
   II. Harley, E.E.
III. S-R009 01 01

David Taylor Model Basin. Report 1564.
PERFORMANCE OF VERTICAL AXIS (CYCLOIDAL) PRO-
PELLERS CALCULATED BY TANIGUCHI'S METHOD, by
W.L. Haberman and E.E. Harley. Nov 1961. iv, 39p. illus.,
graphs, refs.   UNCLASSIFIED

A method proposed by Taniguchi has been used to compute the
performance characteristics of vertical axis propellers having
cycloidal blade motion and semi-elliptic blades. Numerical re-
sults of thrust and torque coefficient and efficiency are presented
for a wide range of advance coefficients, maximum blade angle,
and blade solidity.
Good agreement between the experimental performance and the
computed results is obtained for two, three, and six-bladed
cycloidal propellers.

1. Cycloidal propellers--
   Performance--Analysis
   I. Haberman, W.L.
   II. Harley, E.E.
III. S-R009 01 01

David Taylor Model Basin. Report 1564.
PERFORMANCE OF VERTICAL AXIS (CYCLOIDAL) PRO-
PELLERS CALCULATED BY TANIGUCHI'S METHOD, by
W.L. Haberman and E.E. Harley. Nov 1961. iv, 39p. illus.,
graphs, refs.   UNCLASSIFIED

A method proposed by Taniguchi has been used to compute the
performance characteristics of vertical axis propellers having
cycloidal blade motion and semi-elliptic blades. Numerical re-
sults of thrust and torque coefficient and efficiency are presented
for a wide range of advance coefficients, maximum blade angle,
and blade solidity.
Good agreement between the experimental performance and the
computed results is obtained for two, three, and six-bladed
cycloidal propellers.

1. Cycloidal propellers--
   Performance--Analysis
   I. Haberman, W.L.
   II. Harley, E.E.
III. S-R009 01 01

David Taylor Model Basin. Report 1564.
PERFORMANCE OF VERTICAL AXIS (CYCLOIDAL) PRO-
PELLERS CALCULATED BY TANIGUCHI'S METHOD, by
W.L. Haberman and E.E. Harley. Nov 1961. v, 39p. illus.,
graphs, refs.   UNCLASSIFIED

A method proposed by Taniguchi has been used to compute the
performance characteristics of vertical axis propellers having
cycloidal blade motion and semi-elliptic blades. Numerical re-
sults of thrust and torque coefficient and efficiency are presented
for a wide range of advance coefficients, maximum blade angle,
and blade solidity.
Good agreement between the experimental performance and the
computed results is obtained for two, three, and six-bladed
cycloidal propellers.

1. Cycloidal propellers--
   Performance--Analysis
   I. Haberman, W.L.
   II. Harley, E.E.
III. S-R009 01 01

UNCLASSIFIED